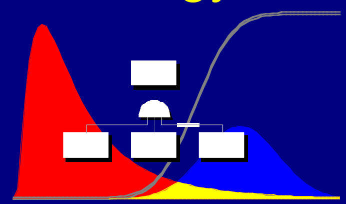
# Early Design Insights
with
# Digital Functional Vehicle

by

Andreas Vlahinos & Tony Markel
National Renewable Energy Laboratory (NREL)



Fuel Cell Technology for Advanced Vehicles

Rochester Institute of Technology

Rochester, New York

April 23-25, 2002

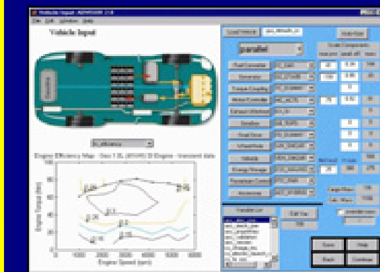
# National Renewable Energy Laboratory (NREL)

- NREL Mission
  - Lead the nation toward a sustainable energy future by developing renewable energy technologies, improving energy efficiency, advancing related science and engineering, and facilitating commercialization
- Established in 1977 as Solar Energy Research Institute (Achieved National Laboratory status in 1992)
- One of eleven DOE National Laboratories
- Current staff of approximately 780
- Estimated operating budget of $188M for FY00
- Located in Golden, Colorado, USA (15 miles west of Denver)

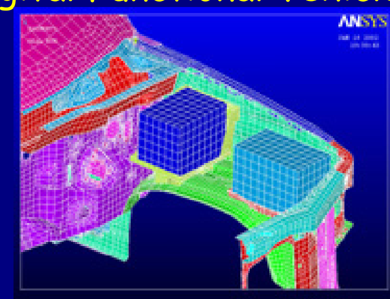



# Hybrid Electric Vehicle Program at NREL Involves 3 Main Areas of Emphasis

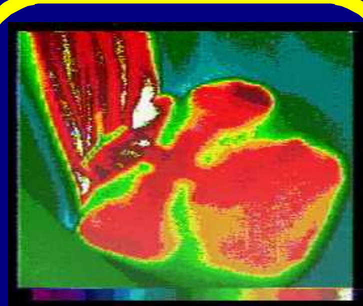
ADVISOR



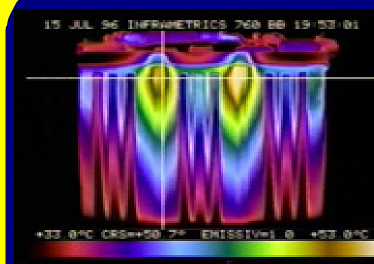
Digital Functional Vehicle




Vehicle Systems Analysis



Vehicle Auxiliary Load Reduction




Battery Thermal Management

**Big 3 Partnership**

**PNGV -> 55 mpg > 80 mpg**

**Multi-Platform, FreedomCAR**



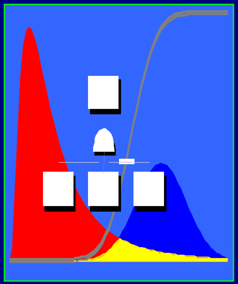
# DOE & Digital Functional Vehicle Objectives

- DOE:

  - Decrease petroleum consumption and emissions of light-duty vehicle transportation while maintaining safety and affordability

- DFV:

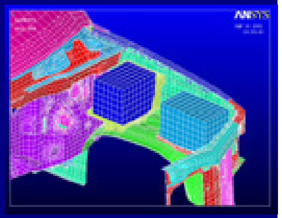
  - Enable and accelerate new fuel efficiency technologies (HEV, Fuel Cells, Manufacturing) by removing technical barriers



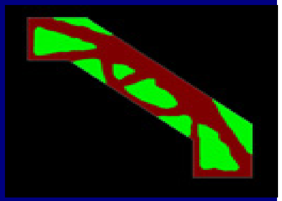
  - Investigate, develop and implement lightweight design processes for achieving improved fuel economy in high volume production vehicles

# Key working strategies to achieve DFV objectives

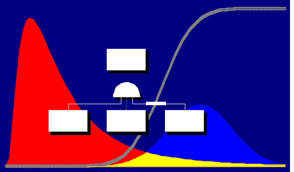
- Work with industry to identify projects with energy savings potential
- Focus on math-based processes in ALL phases of the design process (Conceptual -> CAD -> CAE -> Manufacturing)



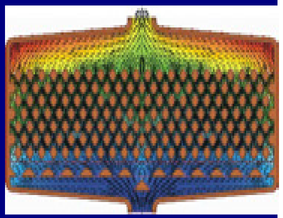
- Utilization of innovative design processes that lead to efficient load path generation (topology optimization, behavioral modeling, etc)



- Ultra lightweight designs that achieve the desired quality level (i.e. 6$\sigma$) via probabilistic modeling of variations

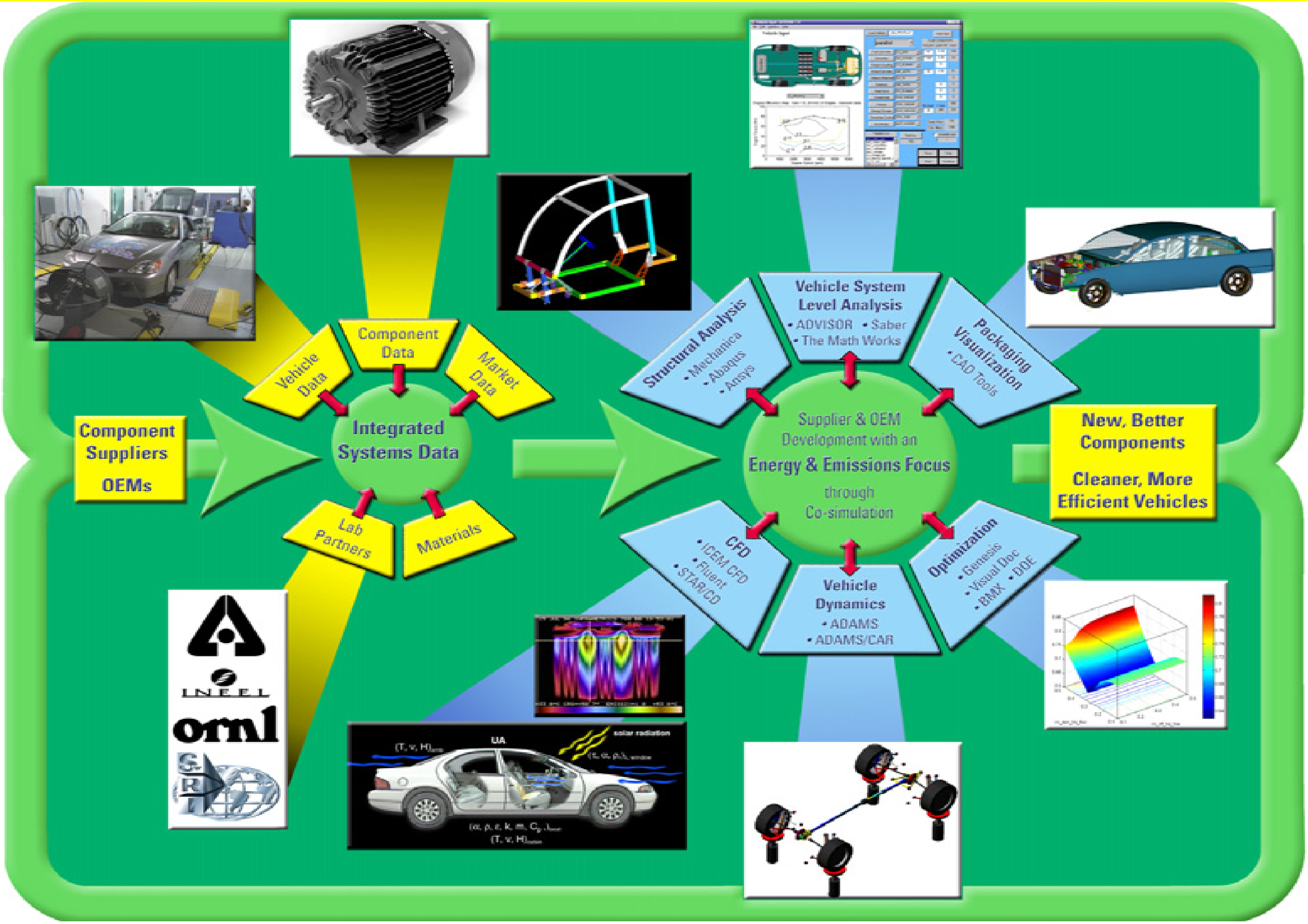


- Utilization of multi-physics optimization to impact, enable and accelerate the implementation of new fuel efficiency technologies

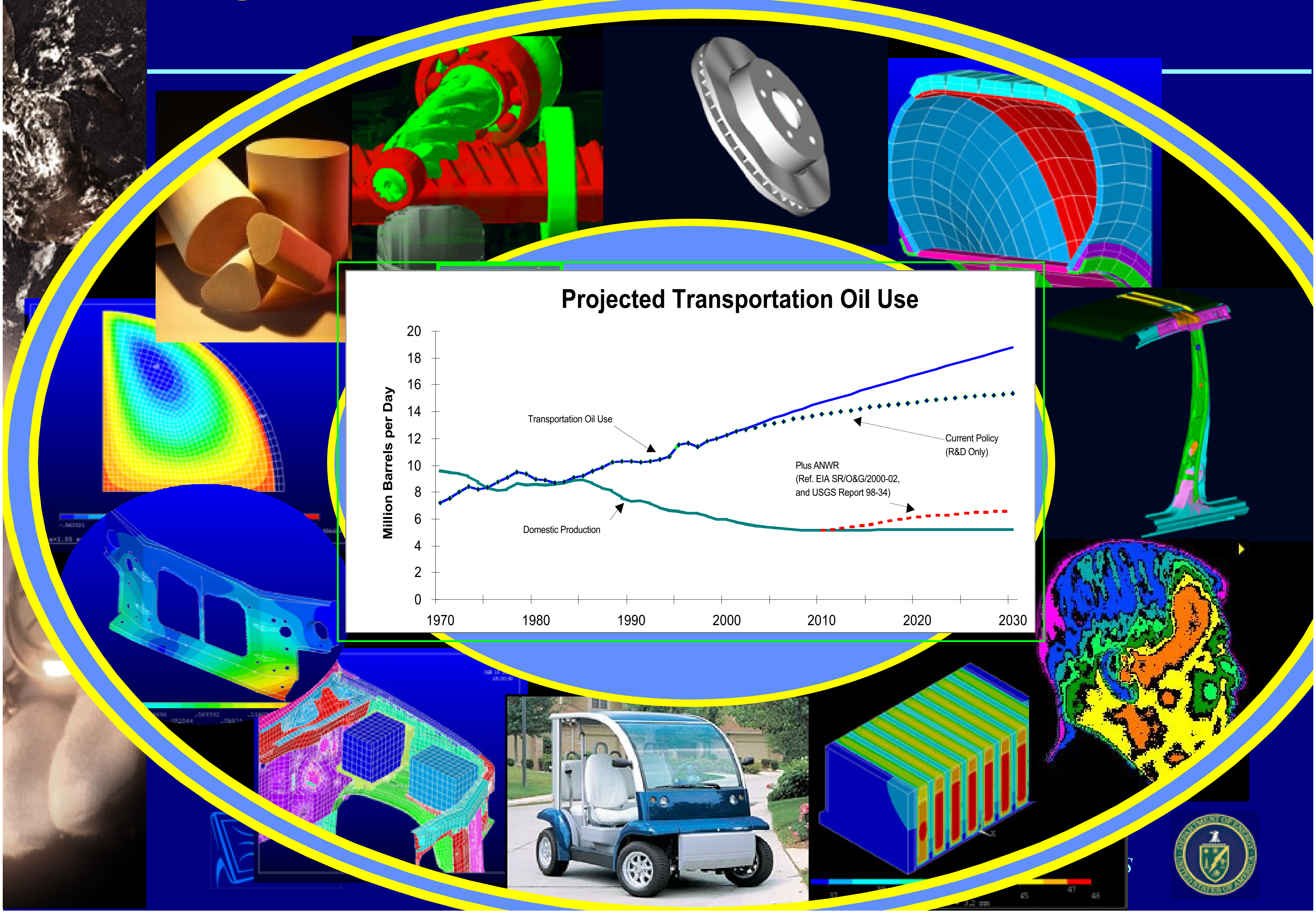


- Technology Transfer to automotive industry

**A collection of integrated software modeling tools and processes that enable the evaluation, design & optimization of new energy-saving automotive technologies such as HEVs and Fuel Cells.**



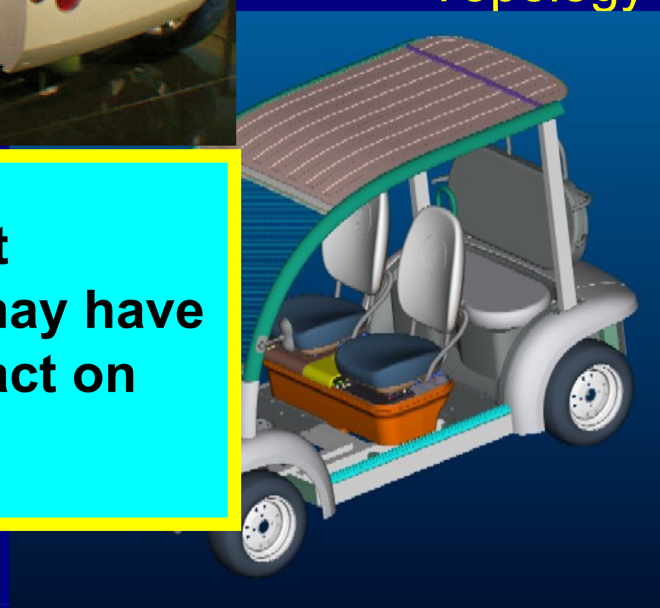
# Digital Functional Vehicle Accomplishments

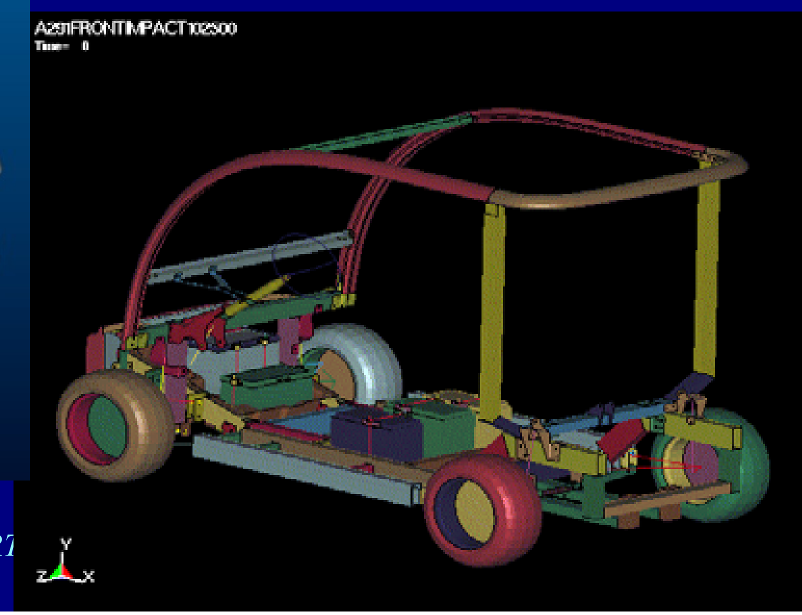


# Rapid Development of FORD Think-mobility NEV

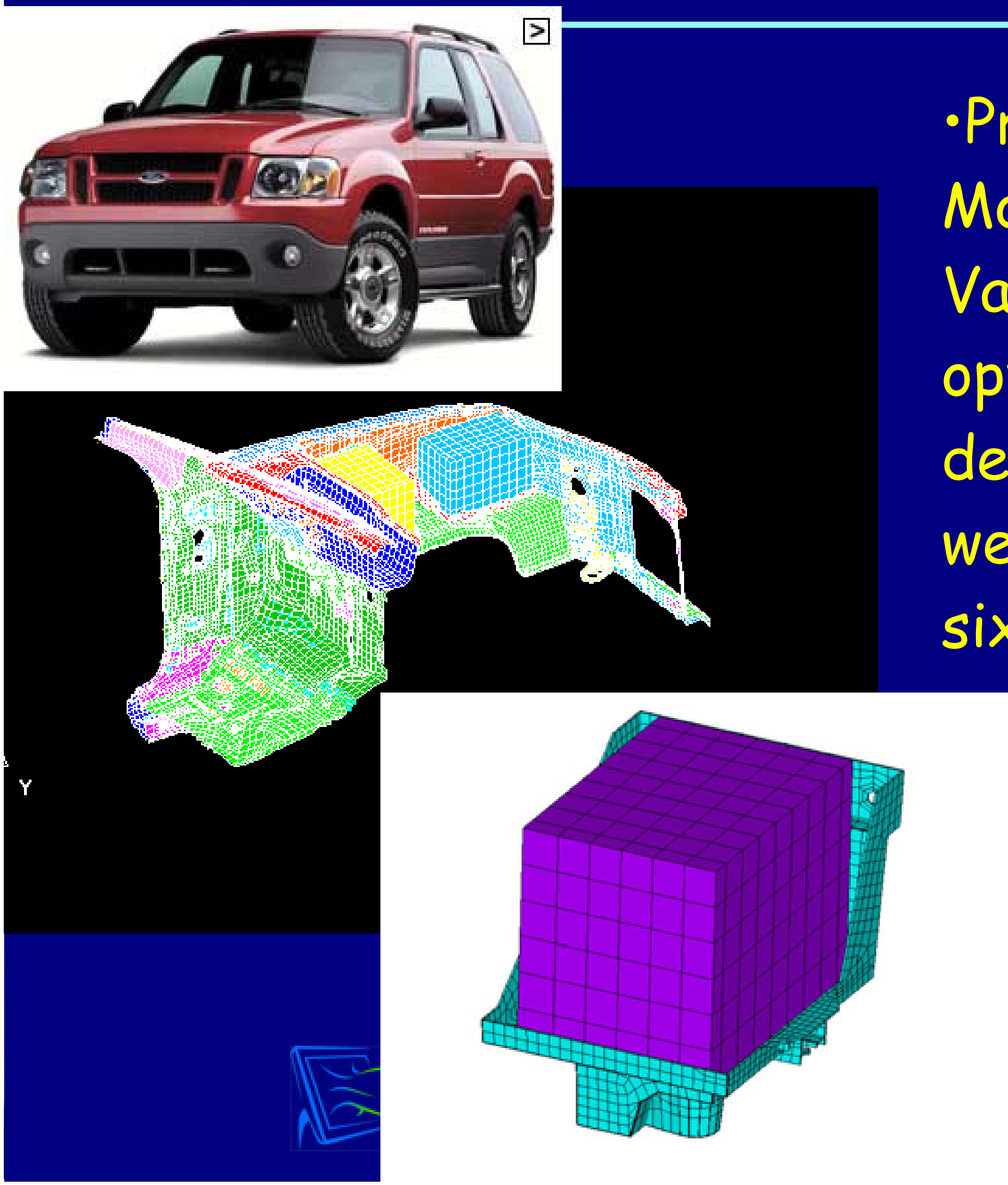
- Suspension Design Process
  - Space Claim Envelop
  - Optimization of Suspension Characteristic
- Chassis Design Process
  - Multi-Functional Attribute Balancing
  - Topology Optimization

**Fuel Cell weight redistribution may have significant impact on safety**

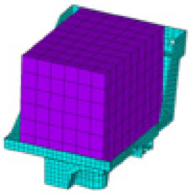




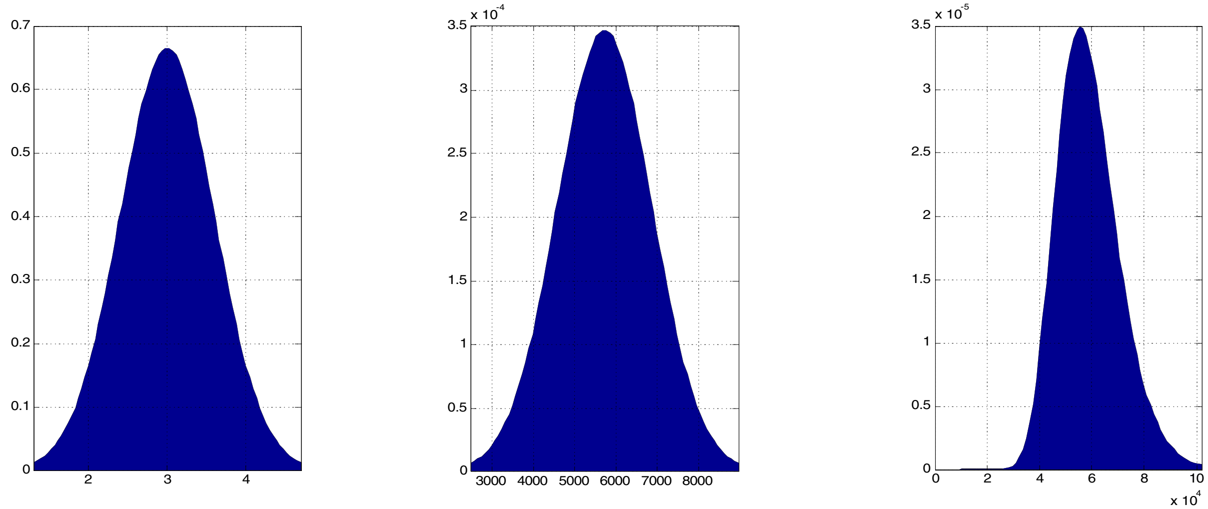
# Body-in-White Weight Reduction via Probabilistic Modeling of Manufacturing Variations




- Probabilistic Durability Modeling of Manufacturing Variations coupled with optimization can avoid over-design, reduce component weight by 17% and achieve six-sigma quality levels



# Probability Distributions of input and output variables

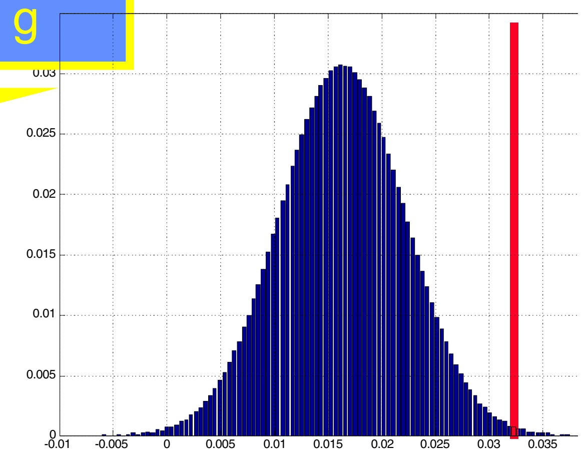



Thickness (3.8-4.2)

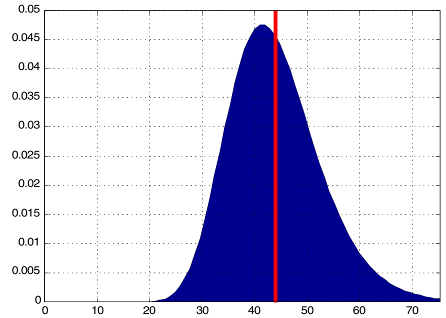
Modulus E

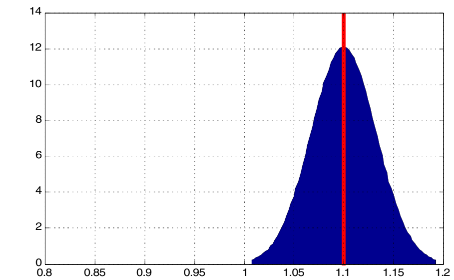
Loading 6 g

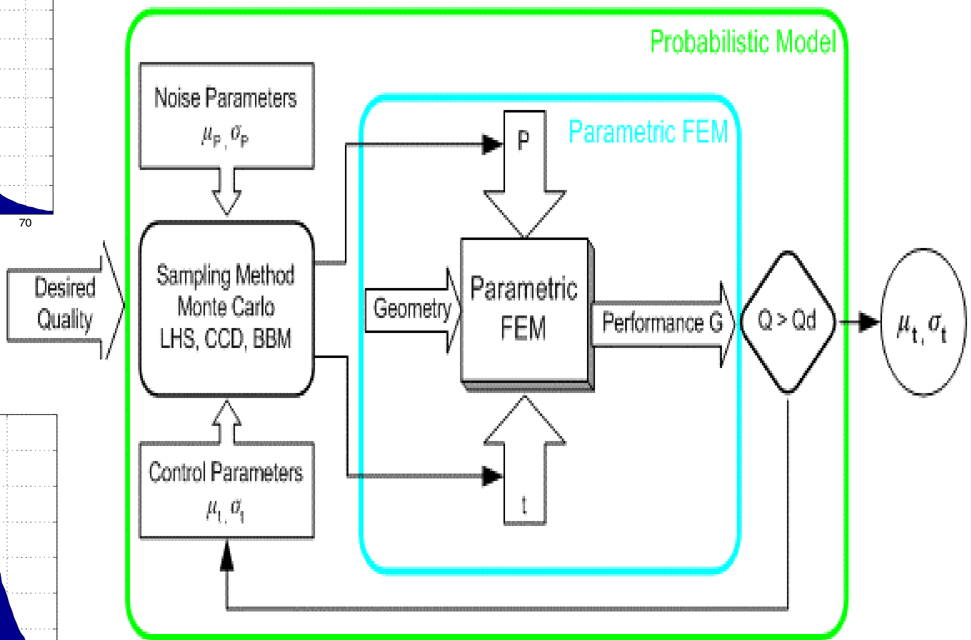
Probabilistic Design Loop

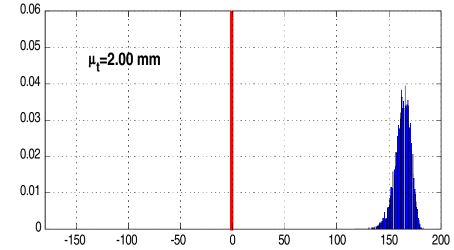


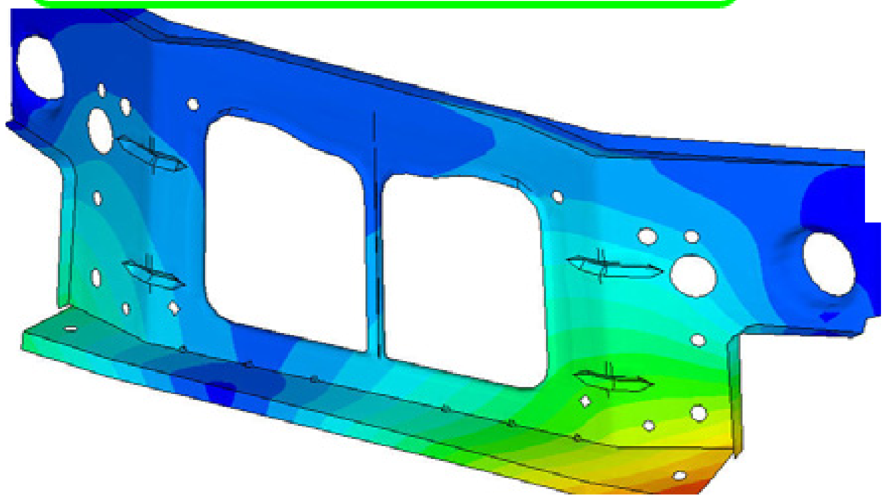
# Robust Optimization for Weight Reduction & 6σ Quality (Workflow)

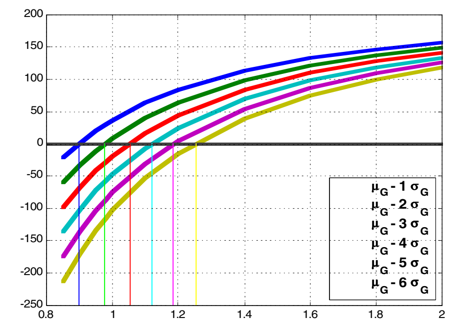




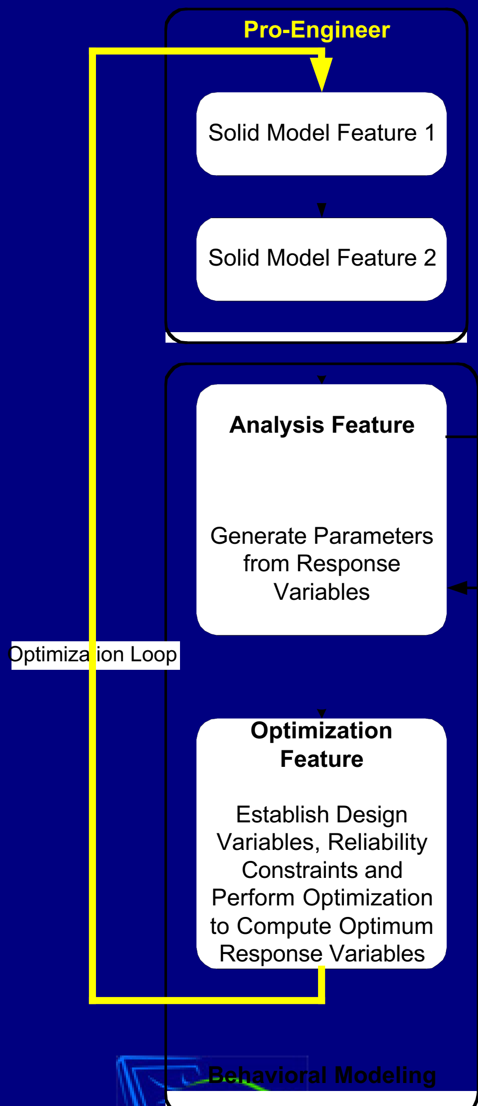


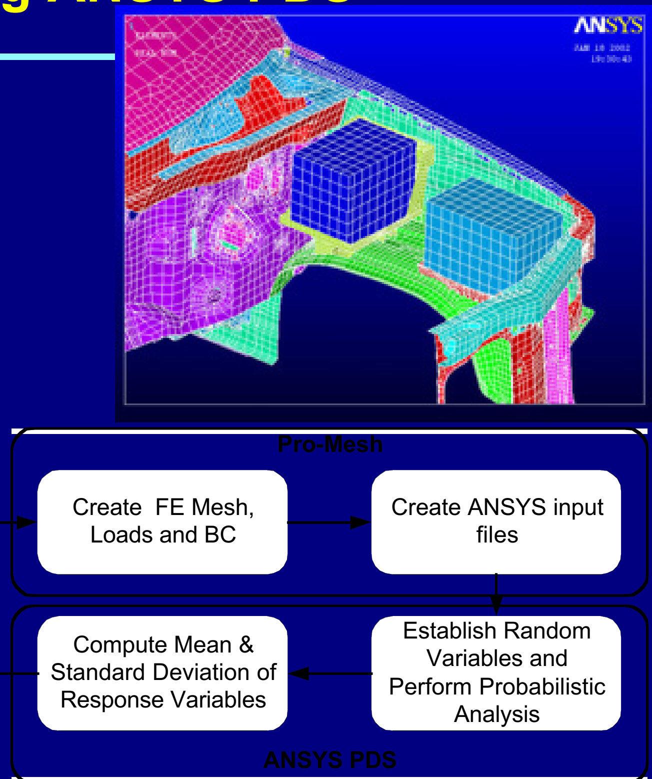



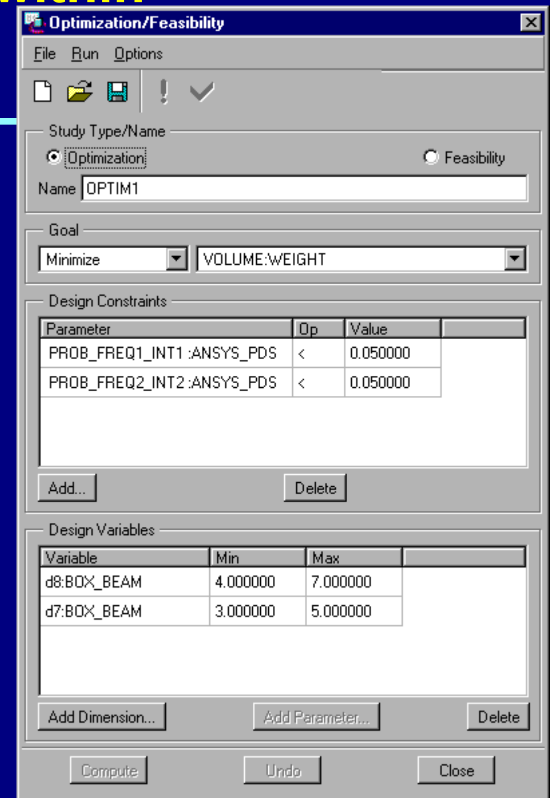





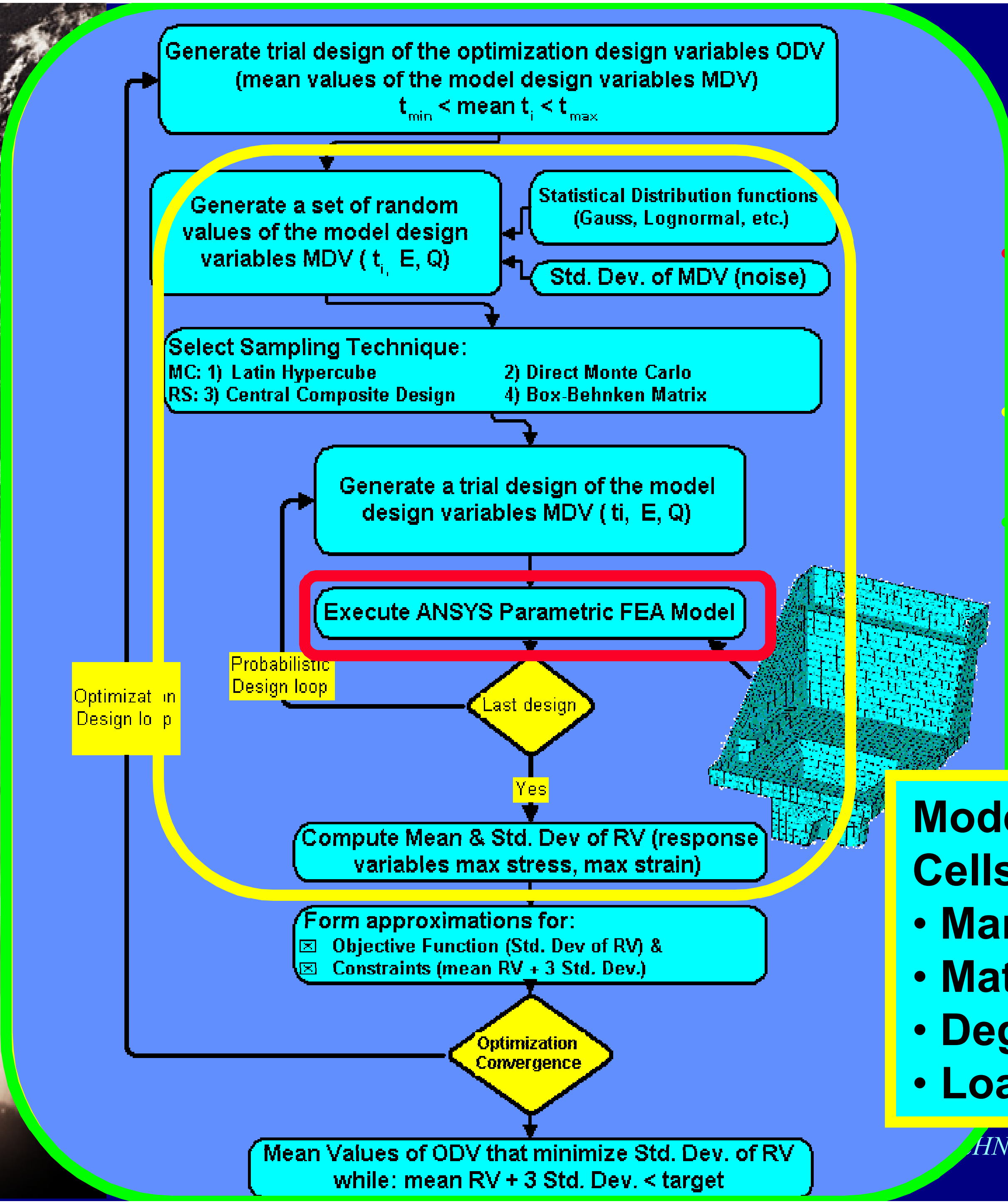
# Workflow for Reliability Based Optimization within Pro/Engineer using ANSYS PDS




- When a Designer makes a change (i.e. hole diameter) the component thickness updates automatically to meet desired quality criteria and **minimize weight**



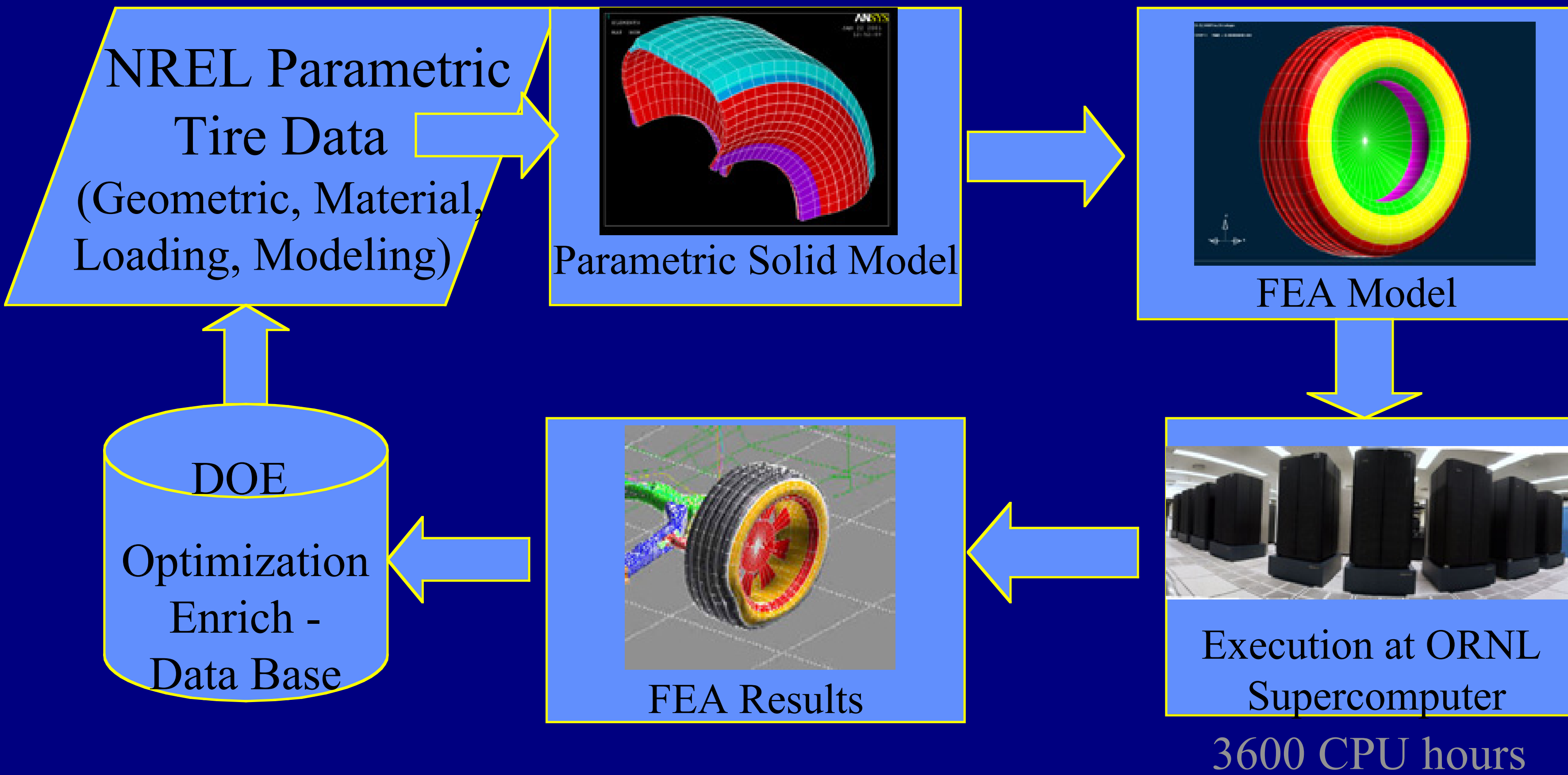

# Workflow

- Automatic, No Manual iteration:
  CAD -> Meshing -> FEA
- Probabilistic Design Loop
- Optimization Loop with reliability constraints

**Modeling Variation of Fuel Cells in:**

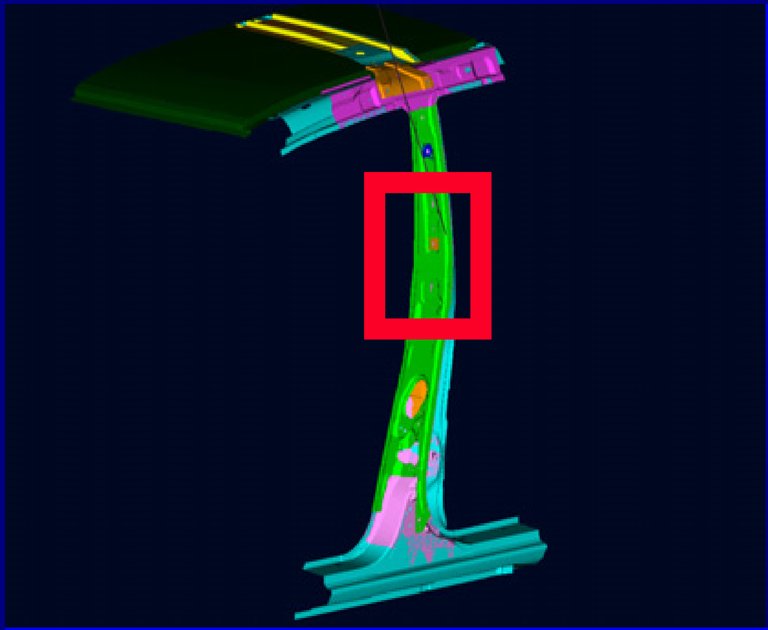
- Manufacturing (t, w, h)
- Material Properties(E,K,p)
- Degradation in time
- Loading Conditions(T,P)

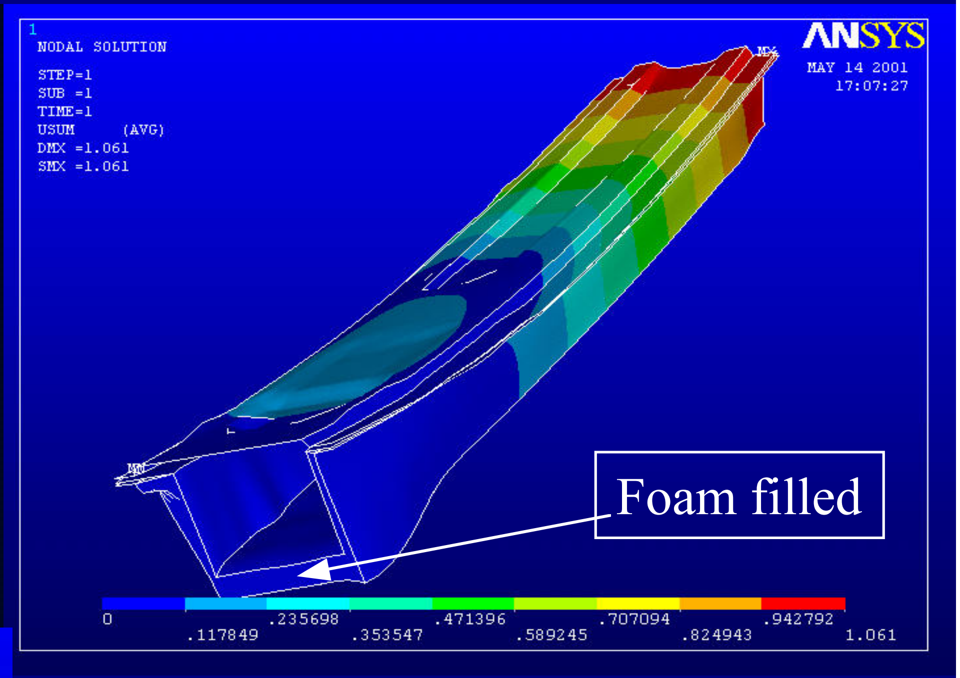
# Advanced Engineering Environment for Tire Modeling at NREL

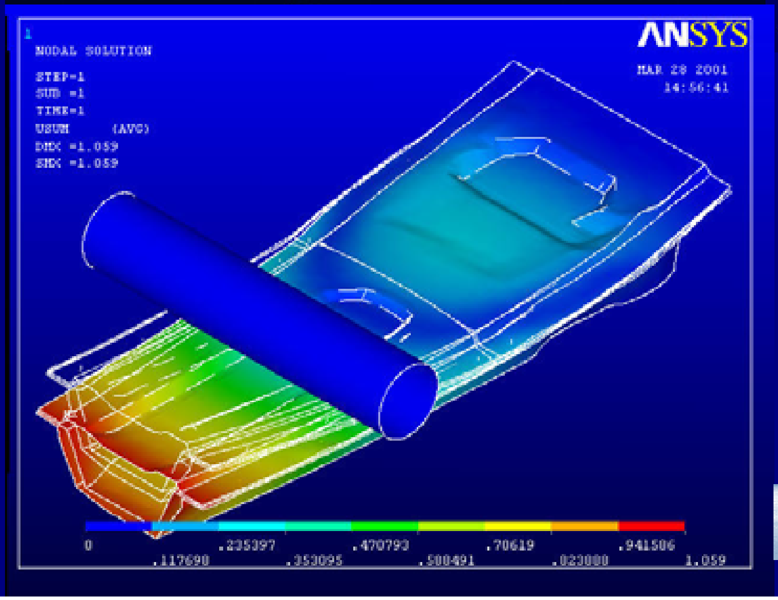



**Selection of key design parameters that are most influential to Fuel Cell attributes & use of optimization algorithms to derive best choice of design parameters**

# Enabling Light Weight Aluminum Auto Body technology by removing the safety barrier



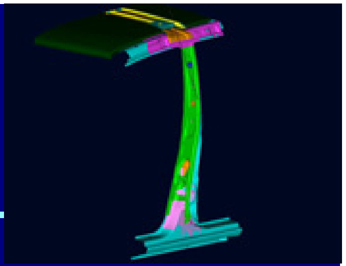


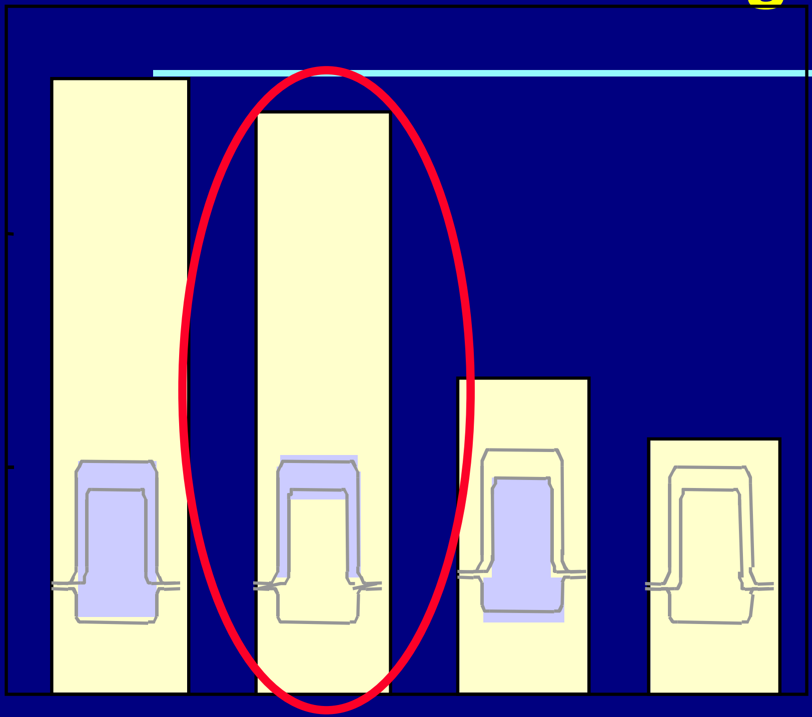




Modular Aluminum Components
Partially Filled
with Structural Foam can
achieve crashworthiness
equivalent to steel structures.

Ford Motor Company SYSTEMS

# Bending Moment Strength





Whole filling

Partial filling
(Outer side)

**Effective Collaboration Model:**
**NREL's Simulation capabilities and partners experimental validation**

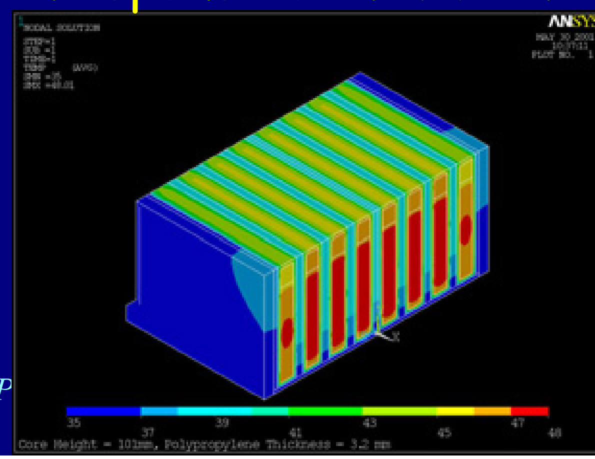
# Process for Battery Thermal Analysis

Thermal modeling & management improves performance of HEV's battery pack.

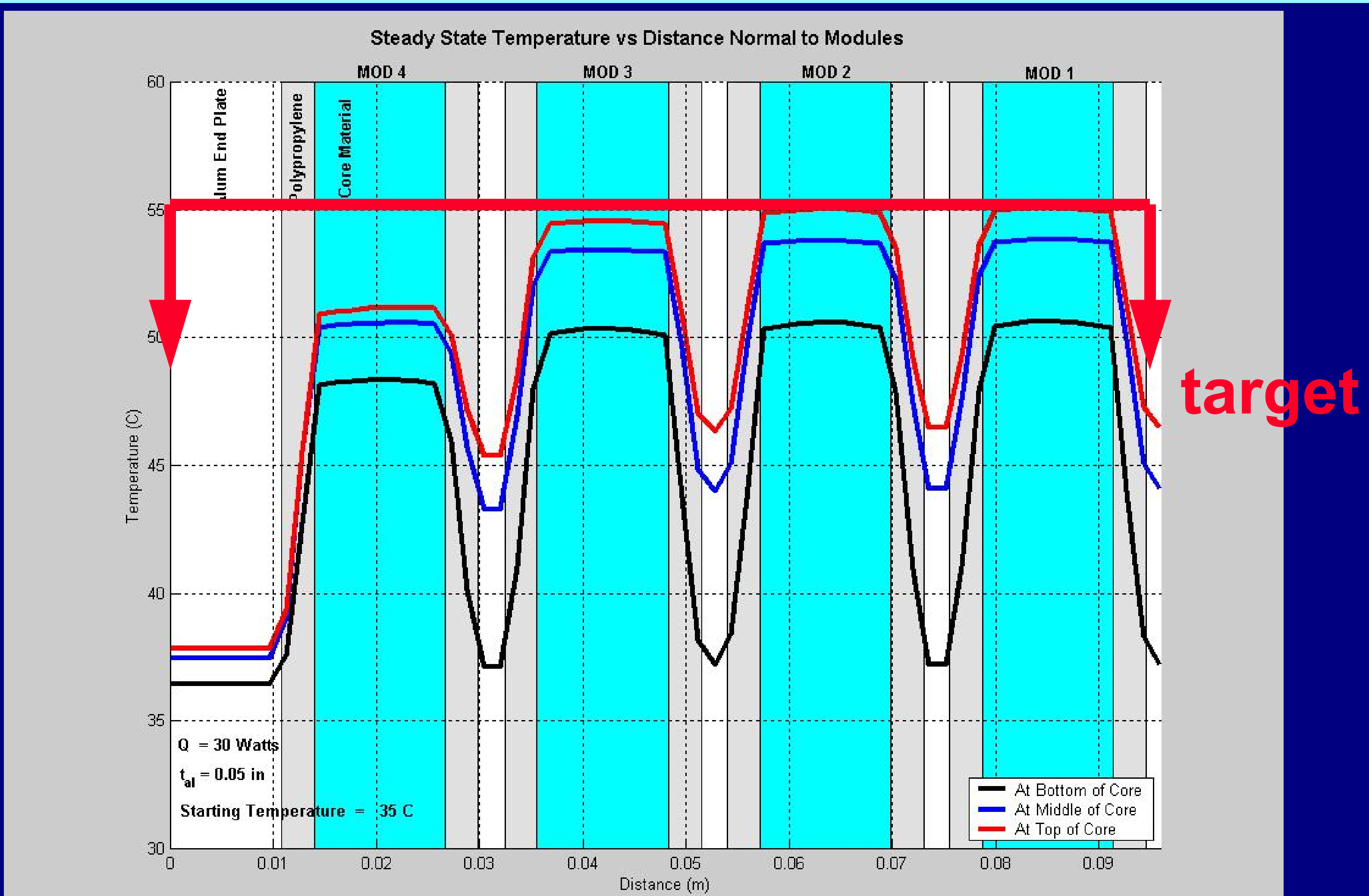
Used NREL's unique analysis and testing capabilities determine the thermal performance and cooling requirements

ADVISOR predicts thermal loading for a realistic drive cycle

Transient thermal FEA predicts transient temperature response over the drive cycle

# Liquid Cooled Design Meets the Max Target




**Similar requirements and thermal analysis process may apply for fuel cell stacks**

# Dissemination of DFV Techniques

02FCC-51

**Energy Efficient Battery Heating in Cold Climates**


Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions

Ahmad A. Pesaran, Ph.D.
...r, National Renewable Energy Laboratory


...nd will take a while to warm up to provide ...efore option 1 may not work fast enough. ... there is energy in the battery, drawing ...ult but power at even low currents can ...ery since the resistance is so high and ...ve heating is high. The engine can also ...ver the on-board generator. A system that ...om the battery for warming it has been ...ntiani and Stuart). For EVs, off-board ...e used to heat batteries electrically.

...f all batteries decreases with temperature ...egrees; at very cold temperatures the ...s to operate properly, which leads to ... HEVs may suffer even more than ...vehicles because their batteries perform ...ng up batteries is essential for achieving

02IBECA-28

**Designing For Six-Sigma Quality with Robust Optimization using CAE**


Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions, LLC

Subhash G. Kelkar, Ph.D.
Staff Technical Specialist, Ford Motor Company


...omotive industry's business model include: ... designs are tailored to focused markets; ... are being manufactured more on a global ...d vehicles are designed increasingly through ...engineering sites around the world.

...issues are addressed early in the design cycle ...ust design is a methodologies. The goal of ...esign is to deliver customer expectations at ...

01IBECA-6

**Body-in-White Weight Reduction via Probabilistic Modeling of Manufacturing Variations**

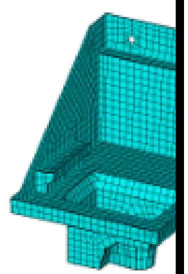

Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions, LLC

Subhash Kelkar, Ph.D.
Staff Technical Specialist, Ford Motor Company


...esponse surface sampling techniques are ...ented in determining the response distribution. ...ma design criteria are e... ...ent and compare this ...ed using the traditional no...

...arametric Determinist...

...s study, the battery tray ...1) was selected. The ...site material SMC and is ...del shown in figure 2).



...1. FE Model Of The Batt...

...ttery is modeled with an el... ...rm density appropriately a... ...weight. The battery is su...

02FCC-68

**Robust Design of a Catalytic Converter with Material and Manufacturing Variations**


Andreas Vlahinos
Principal, Advanced Engineering Solutions, LLC

Danet Suryatama, Mustafa Ullahkhan, Jay T. TenBrink, Ronald E. Baker
DaimlerChrysler Corporation




...ACT

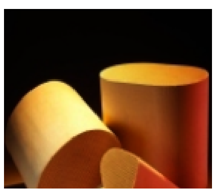

... is robust when the performance targets have ...hieved and the effects of variation have been ...d without eliminating the causes of the ... such as manufacturing tolerances, material ...s, environmental temperature, humidity, ...al wear etc. In recent years several robust ...oncepts have been introduced in an effort to ...ptimum designs and minimize the variation in ...uct characteristics [1,2]. In this study, a ...stic design analysis was performed on a ... converter substrate in order to determine the manufacturing tolerance that results in a robust ... Variation in circularity (roundness) and the ... shear stress of the substrate material were ...ed. The required manufacturing tolerance for a ...esign with 1,2 and 3 sigma quality levels was ...ed. The same manufacturing tolerance for a ... based design with reliability levels of 85%, ...95% was also determined and compared. The ...ogy for implementing robust design used in this ... effort is summarized in a reusable workflow


...UCTION

...esign is a methodology that addresses product

of available resources. The probabilistic design process has not been widely used because it has been intimidating and tedious due to its complexity.

In this research effort, probabilistic modeling of manufacturing and material variations for a catalytic converter substrate was considered. Typical shapes of catalytic converter substrates are shown in Figure 1. The substrate used in this study has a cylindrical cross section and is enclosed in a cylindrical steel cover. If the substrate is not a perfect cylinder the steel cover applies a non-uniform pressure along the circumference. Assuming that the maximum diameter of the substrate is $\Phi_{max}$ and the minimum diameter is $\Phi_{min}$, we can characterize the variation in circularity or roundness $\delta$ with their difference $\delta = \Phi_{max} - \Phi_{min}$. Due to manufacturing variations $\delta$ is considered a random input variable.



**Reliability Based Optimization within the CAD Environment**

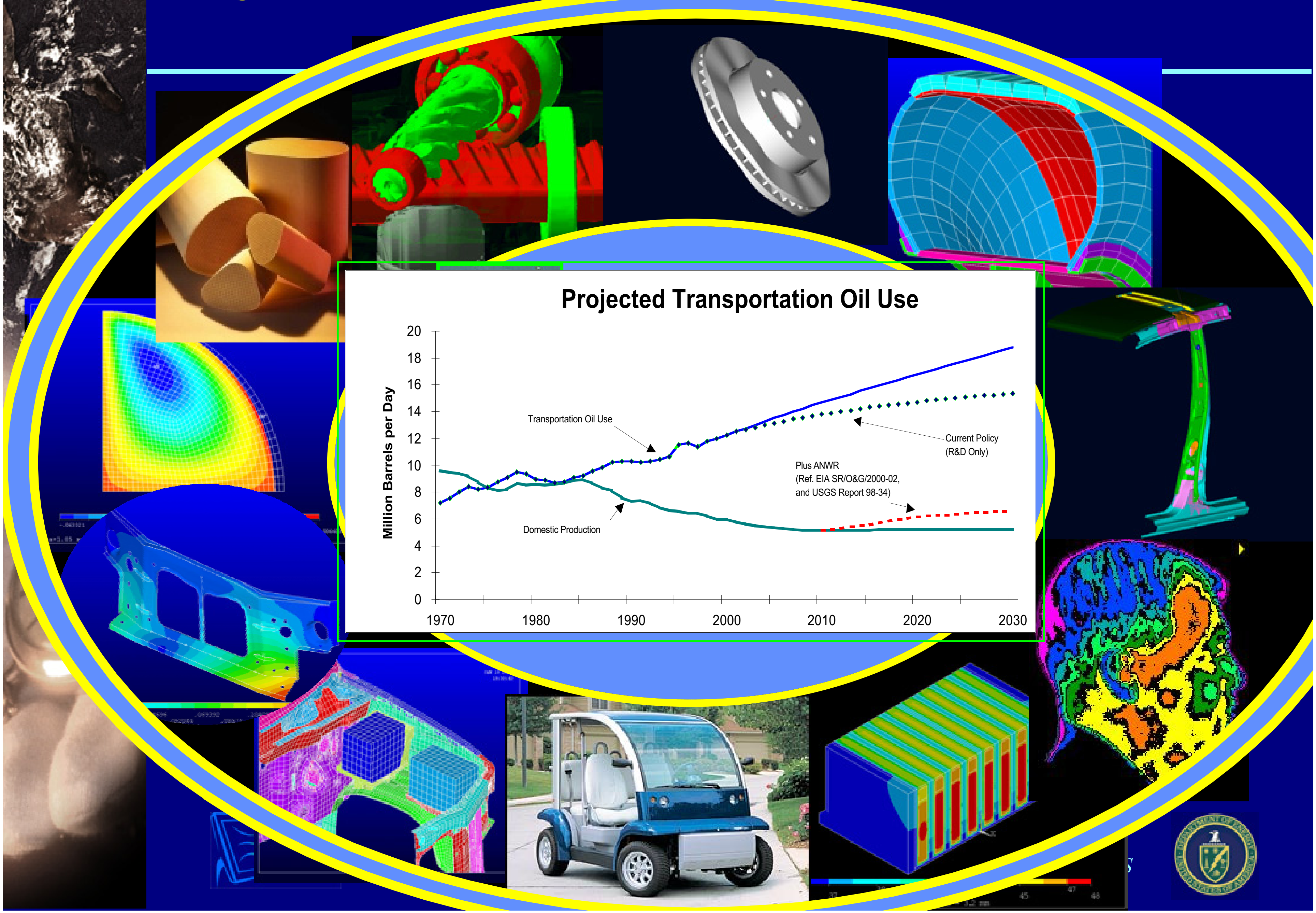

Andreas Vlahinos
Advanced Engineering Solutions, LLC
Subhash Kelkar
Ford Motor Company
Stefan Reh, Robert SeCaur, Steve Pilz
ANSYS Inc.


**Abstract**


Great advances have been achieved over the last two decades in the design process, yet in many industries, this process is still executed by deploying traditional methods. A new method that is flexible enough to accommodate potentially contradictory design requirements such as cost, performance, aesthetics, safety, life cycle, and environmental impacts is being sought by industry leaders seeking an advantage over technically less adept competitors.

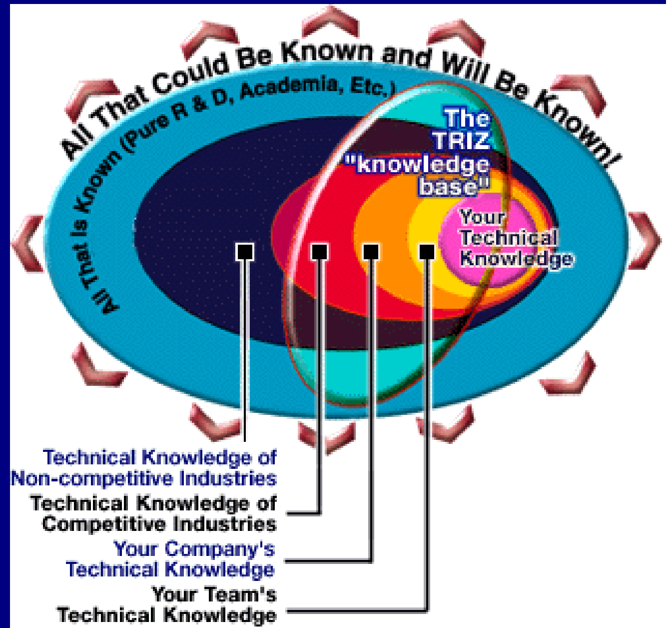
Simulation, modeling, safety and costing tools have improved dramatically in the past decade. What is missing is a workable synergy between these tools. Used separately, these individual tools require several manual iterations to attain the optimum design. An intelligent modeling process for integrating the ...

# Digital Functional Vehicle Accomplishments

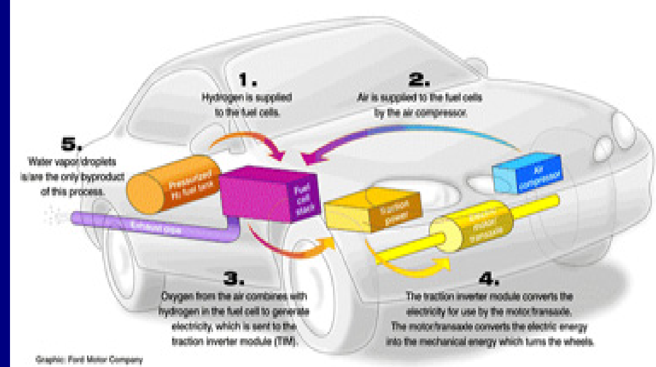


# Conceptual Design Fuel Cells

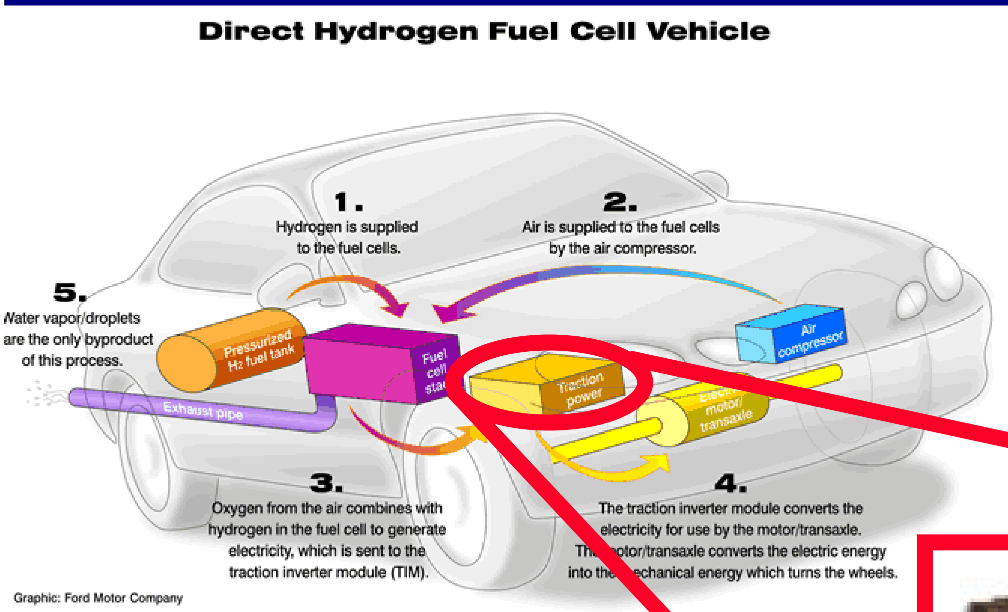
- Conceptual Design Optimization of the fuel cell power systems
  - Identify the components and their function of a fuel cell power system
  - Perform TRIZ Functional Analysis based on the Theory of Inventive Problem Solving
  - Utilize the TRIZ technical knowledge base
  - Generate a set of recommendations for making the system simpler and optimal



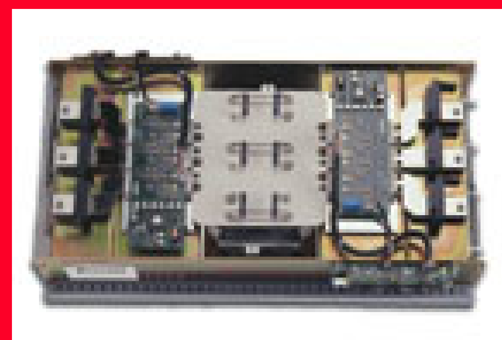

Direct Hydrogen Fuel Cell Vehicle

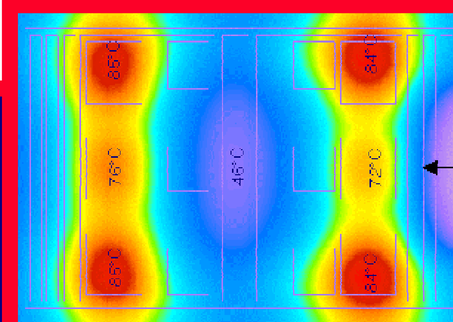


# Automotive Integrated Power Modules (AIPM)

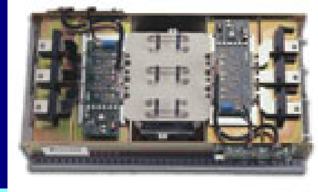



Critical enabling technology for commercialization of HEV & Fuel Cell powered vehicles





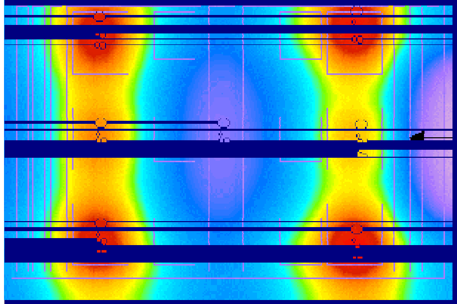
# Automotive Integrated Power Modules (AIPM)



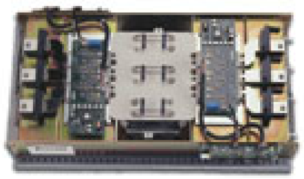
Critical enabling technology for commercialization of HEV & Fuel Cell powered vehicles

## Technical Challenges for AIPM

- Cost
- Reliability and Robustness
- Packaging, Volume & Weight
- Thermal Management

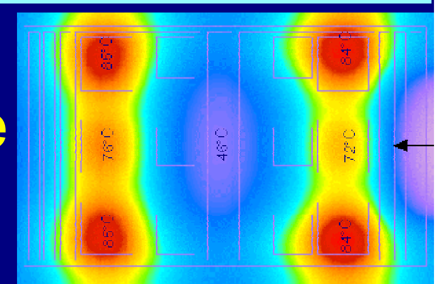


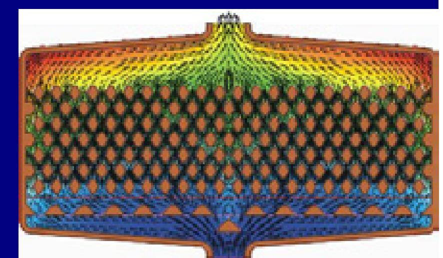
  - Current thermal management techniques are inadequate to dissipate heat in high-power-density systems
  - Innovative Thermal Management Techniques for Fuel Cell Vehicle Traction Inverter Module

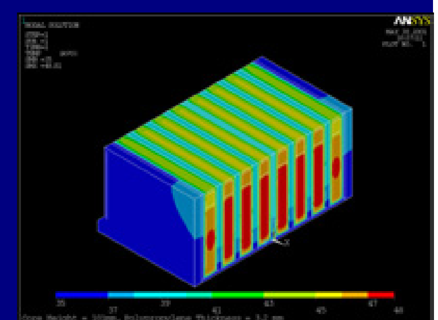


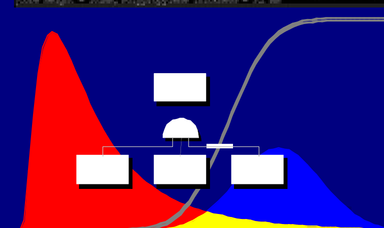
# Innovative Thermal Management Techniques for Fuel Cells

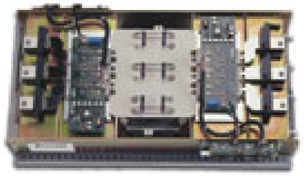
- Uniform cooling is necessary to avoid material degradation and premature failure
- Need for a novel heat exchanger to efficiently remove heat from AIPM and reject it into the vehicles coolant loop with minimum cost, volume and pressure drop
- NREL's experimental and Multi-Physics simulation capabilities ideal for design optimization of AIPM and fuel cell cooling plates
  - TRIZ, CAD, structural, thermal, CFD, Durability, DOE, Probabilistic Design, Multi-disciplinary optimization





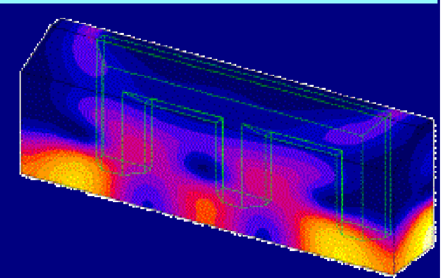


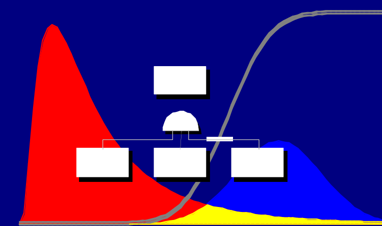


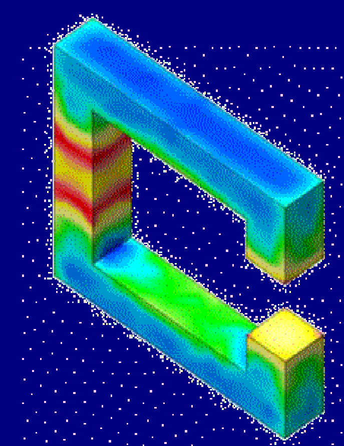


# Multi-Physics Simulation Techniques

- Reduction of inverter parasitic inductance necessary to develop an energy efficient AIPM
- Low stray inductance required to minimize electrical and mechanical stress on semiconductor devices
- Investigate, develop and implement Electromagnetic FEA based techniques to evaluate inverter parasitic inductance
- Selection of key design parameters that are most influential to parasitic inductance & use of optimization algorithms to derive best choice of design parameters (AEE)

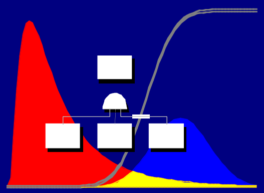




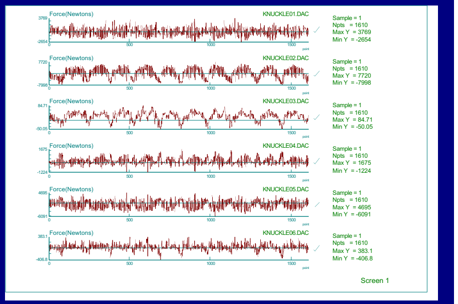


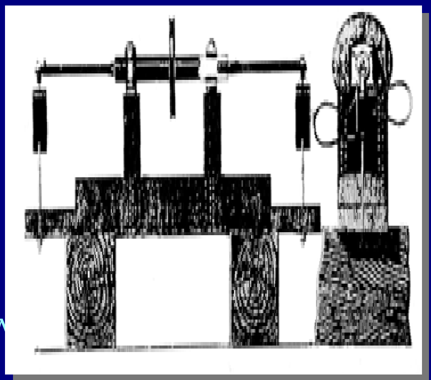
# Reliability and Robustness of Fuel Cells for Automotive Environments

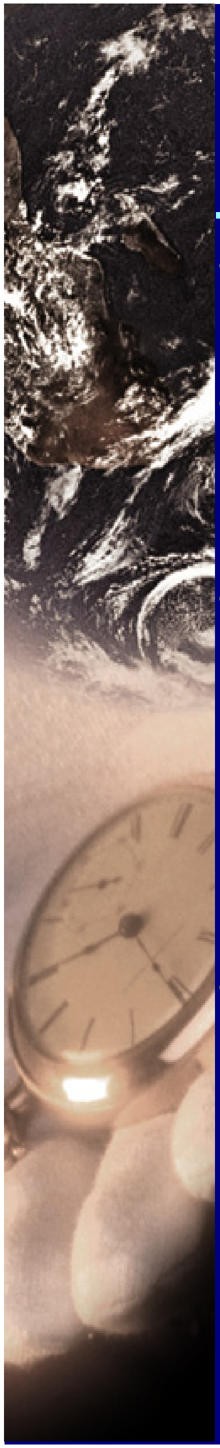
- Existing electric machinery is not rugged enough for the harsh automotive environment
- Failure under a repeated load which never reaches a level sufficient to cause failure in a single application
- Techniques for predicting the durability of proposed Traction Inverter Modules by means of a "digital prototype" simulation
  - Solder joint reliability
  - Electrolytic capacitors
  - Power electronic assemblies



- Fuel Cell Stack Durability
  - Degradation Mechanisms (mechanical, chemical, etc.)
  - Failure mechanisms (layer delamination, membrane holes, etc.)

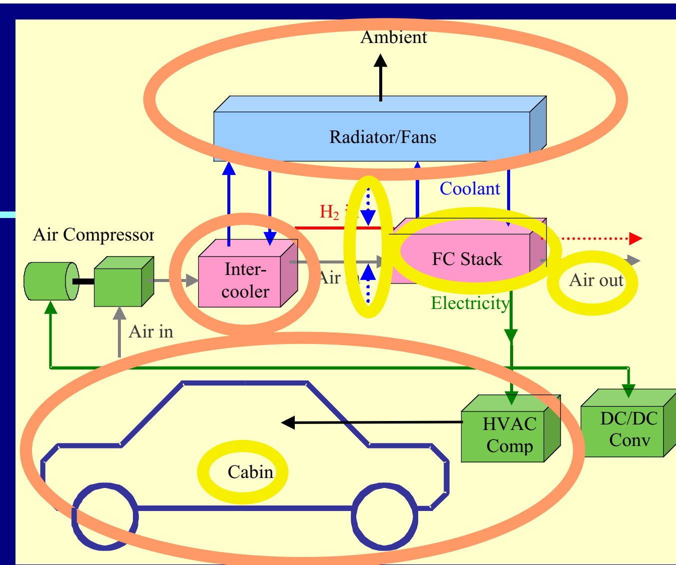


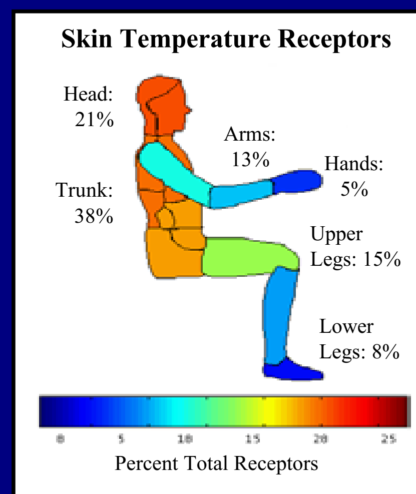


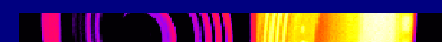


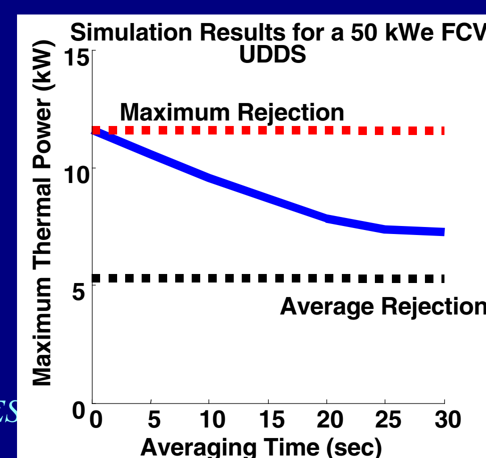
# Cabin Comfort & FC

- Conceptual Cabin & FC System Thermal & Water Management
- Goals
  - Increase stack efficiency & fuel economy, lower cost
  - Reduced auxiliary loads
- Tools & Techniques
  - Thermal Comfort
  - Heat-generated cooling
  - Air compressors
  - Thermal Damper



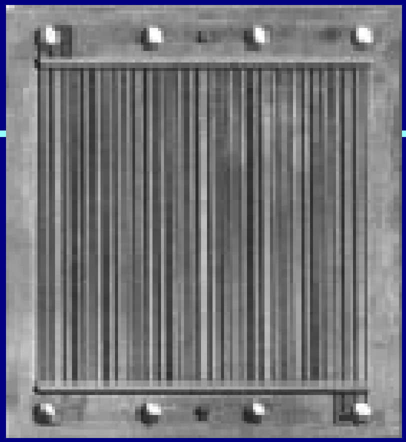



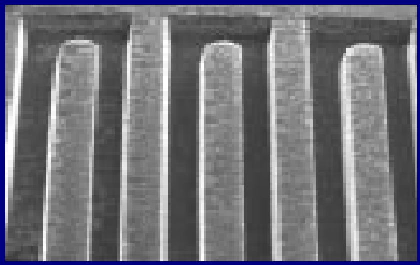



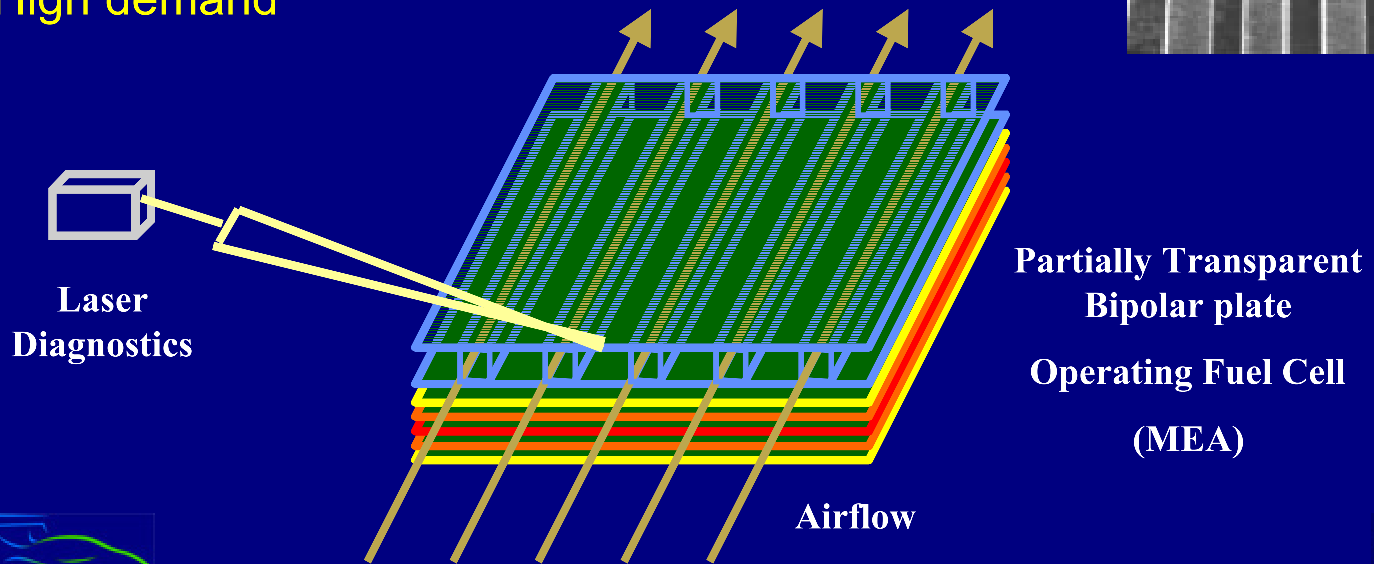


# Local Fuel Cell Measurements Future Work

- Objective
  - Model validation
  - Improved cathode flow field design
- Spatial & temporal measurement of FC
  - Gaseous concentrations, velocities & temperatures
  - Liquid water transport
  - Flow visualization
- Requires at least partially transparent bipolar plates
- High demand

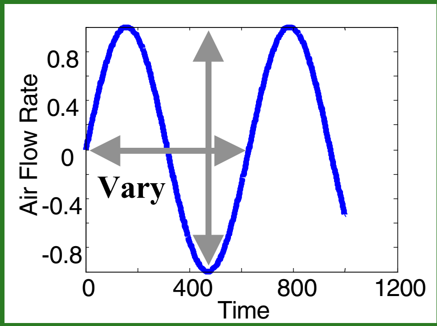




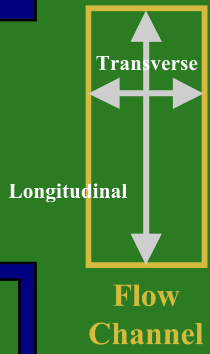


# Reduce Required FC Air Flow
# Future Work

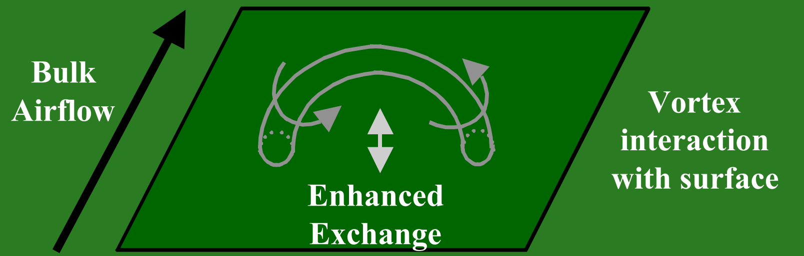
- Improve fuel cell performance & reduce required airflow
  - Increase exchange rate of air and water at cathode
- Techniques
  - Pulsating airflow period and amplitude




  - Acoustic excitation
    - Resonant vortex amplification
    - Resonant channel

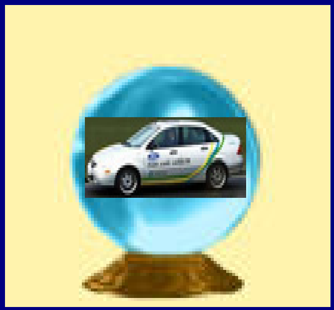




  - Vortex/surface interaction dynamics



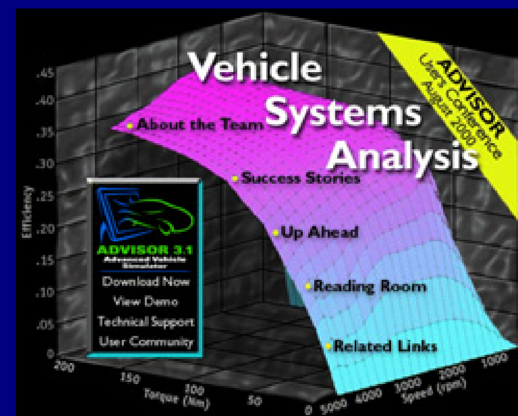
# Early Design Insights with Digital Functional Vehicle

- Integrating digital prototyping and optimization techniques across multiple disciplines in research and development process can:
  - Evaluate the feasibility of a potential new design without physical prototypes
  - Improve quality while achieving multi-attribute goals
  - Reduce development costs and time
  - Improve coordination of physical test and measurement
  - Enable and accelerate new technologies by removing technical barriers



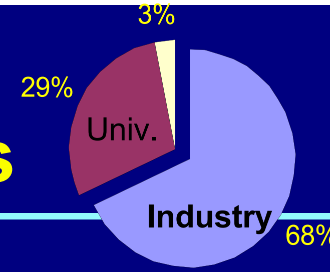
# Background on ADVISOR

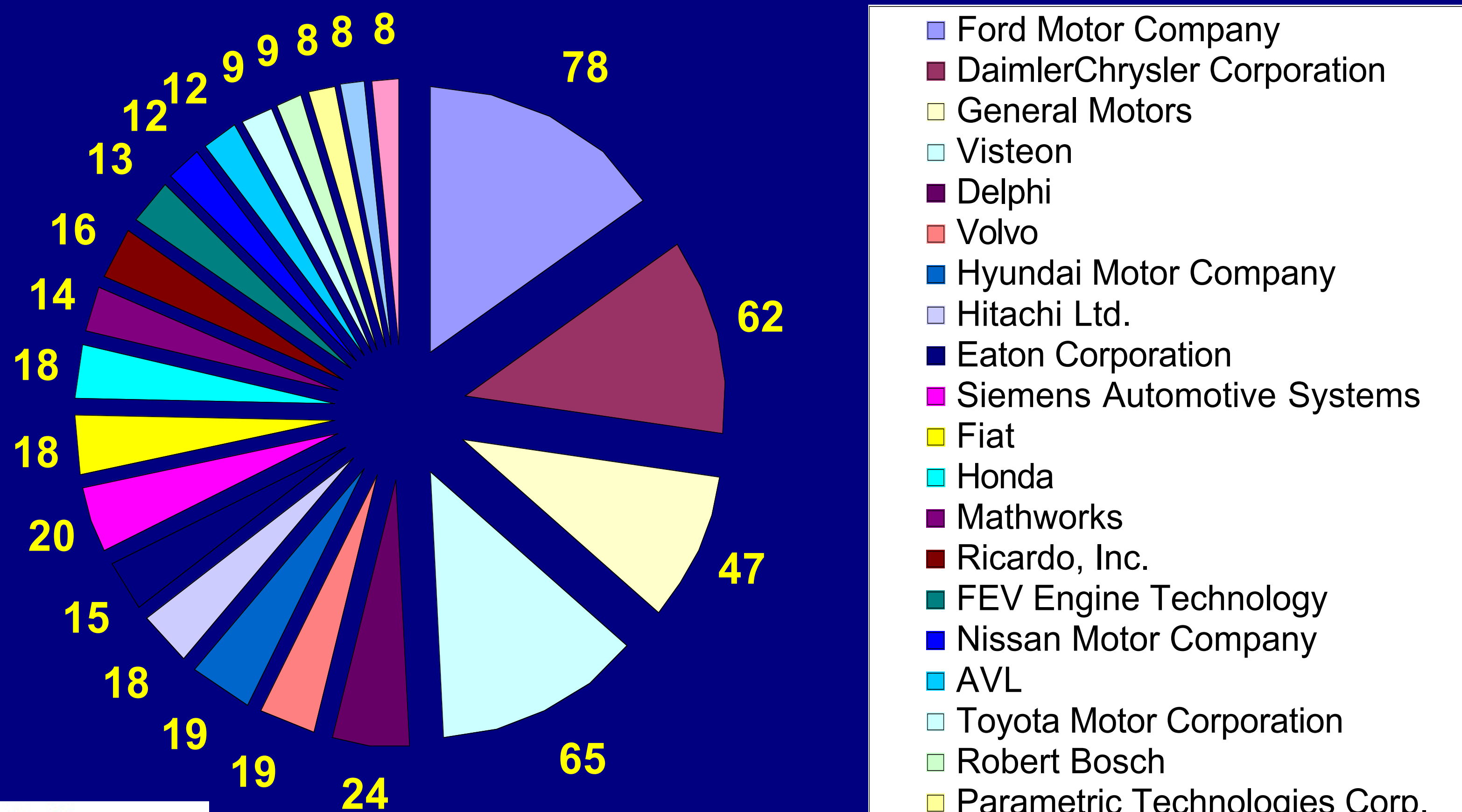
- ADVISOR = ADvanced VehIcle SimulatOR
  - simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell)
- ADVISOR was created in 1994 to support DOE Hybrid Program at NREL

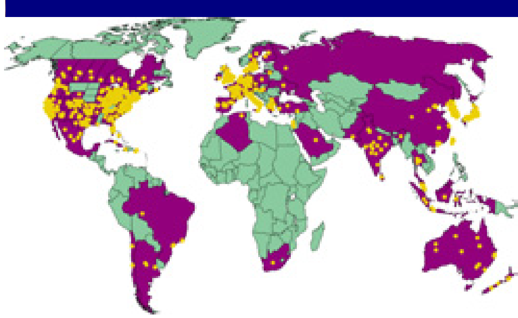



- Released on vehicle systems analysis web site for free download in September, 1998 (www.nrel.gov/transportation/analysis)
- Downloaded by over 4500 people around world
- Users help provide component data and validation, feedback for future development
- Have held 2 User Conferences in last two years

# 2/3 of Users are from Industry, All Major Auto OEMs & Suppliers



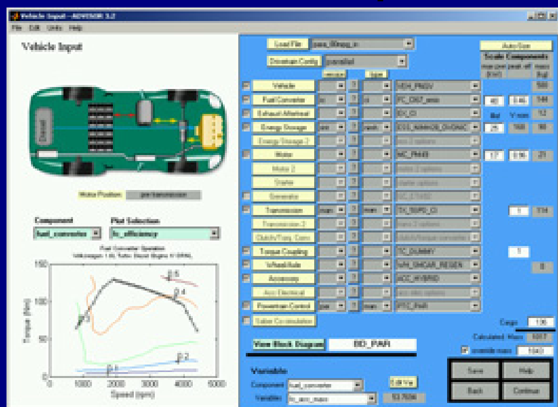



**Legend includes organizations with 8 or more users since v2.0**

**As of 3/19/02**

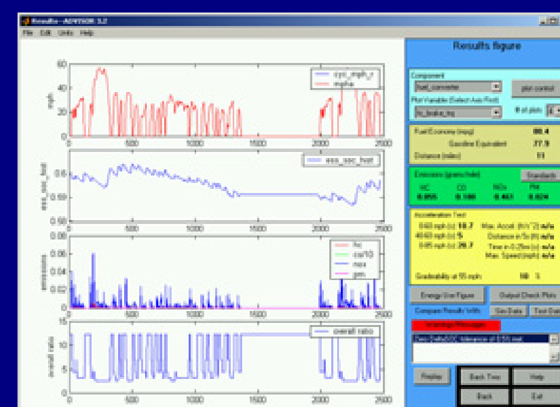
# Three Main GUI Screens (Roadmap)

## Vehicle Input



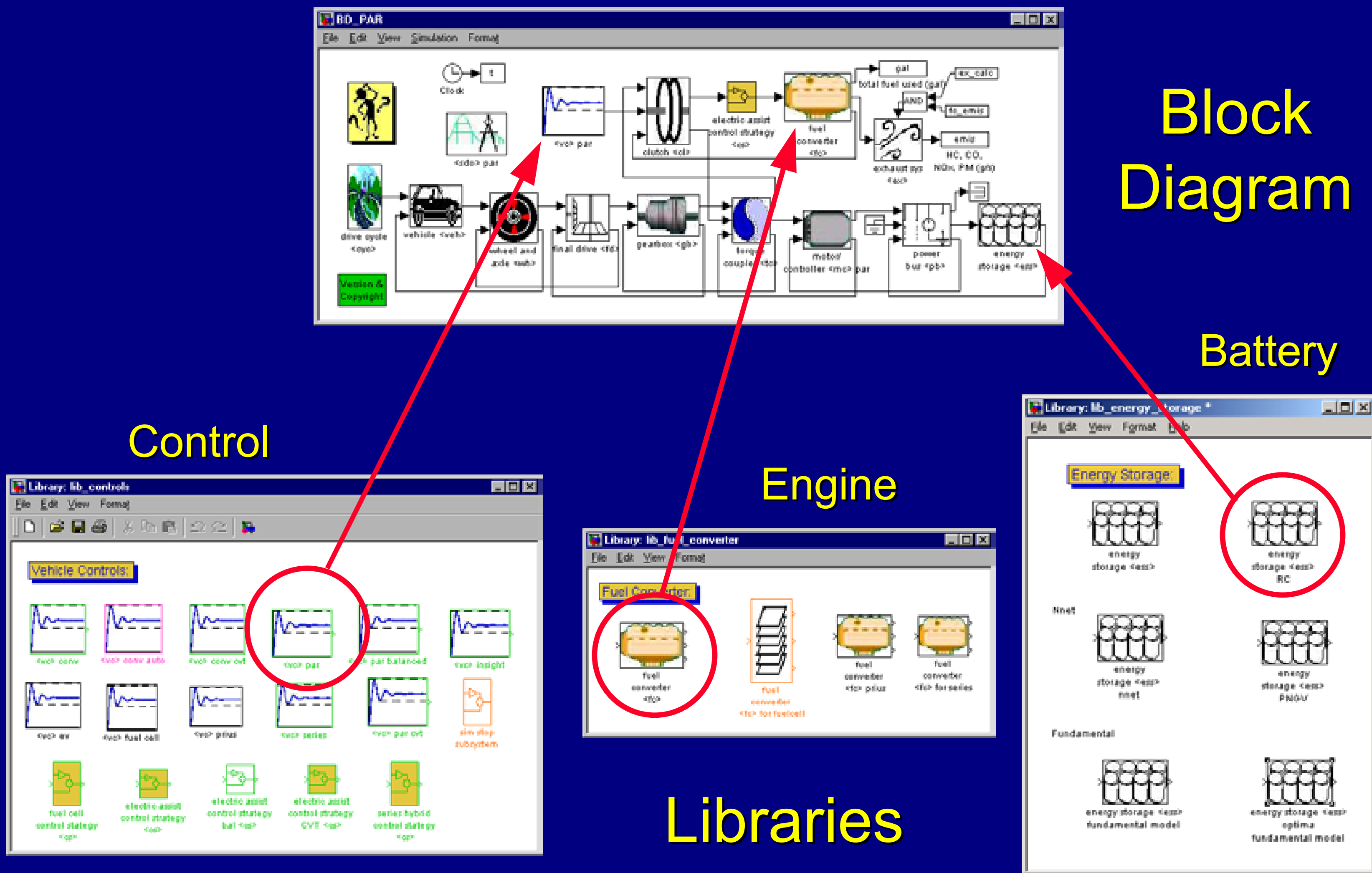
## Simulation Setup

## Results



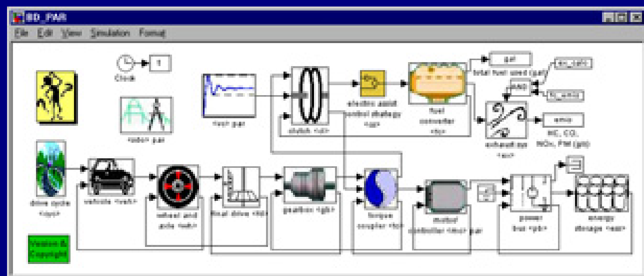
# ADVISOR Demonstration

# Basic Structure (models)

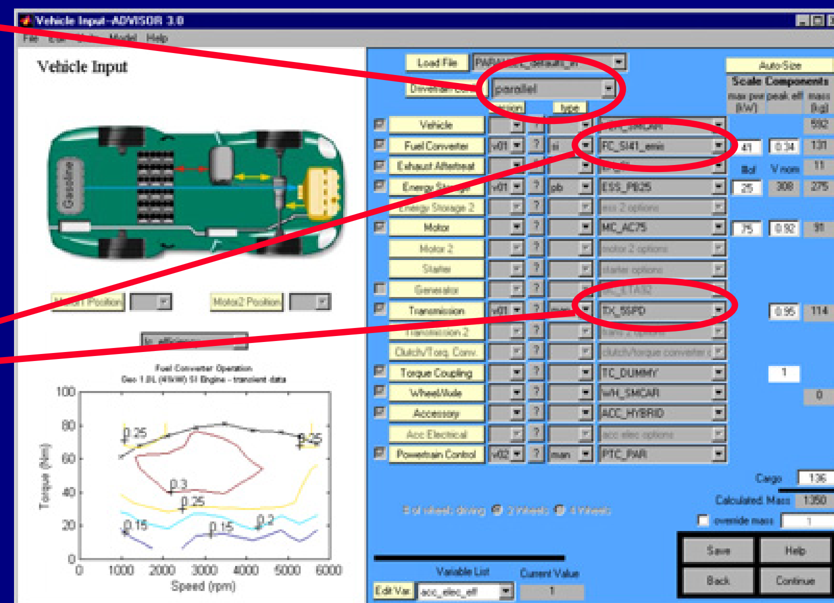


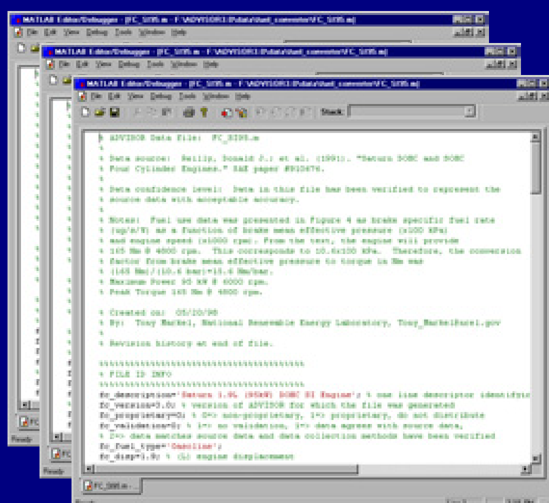
# Basic Structure (database)

Block Diagram



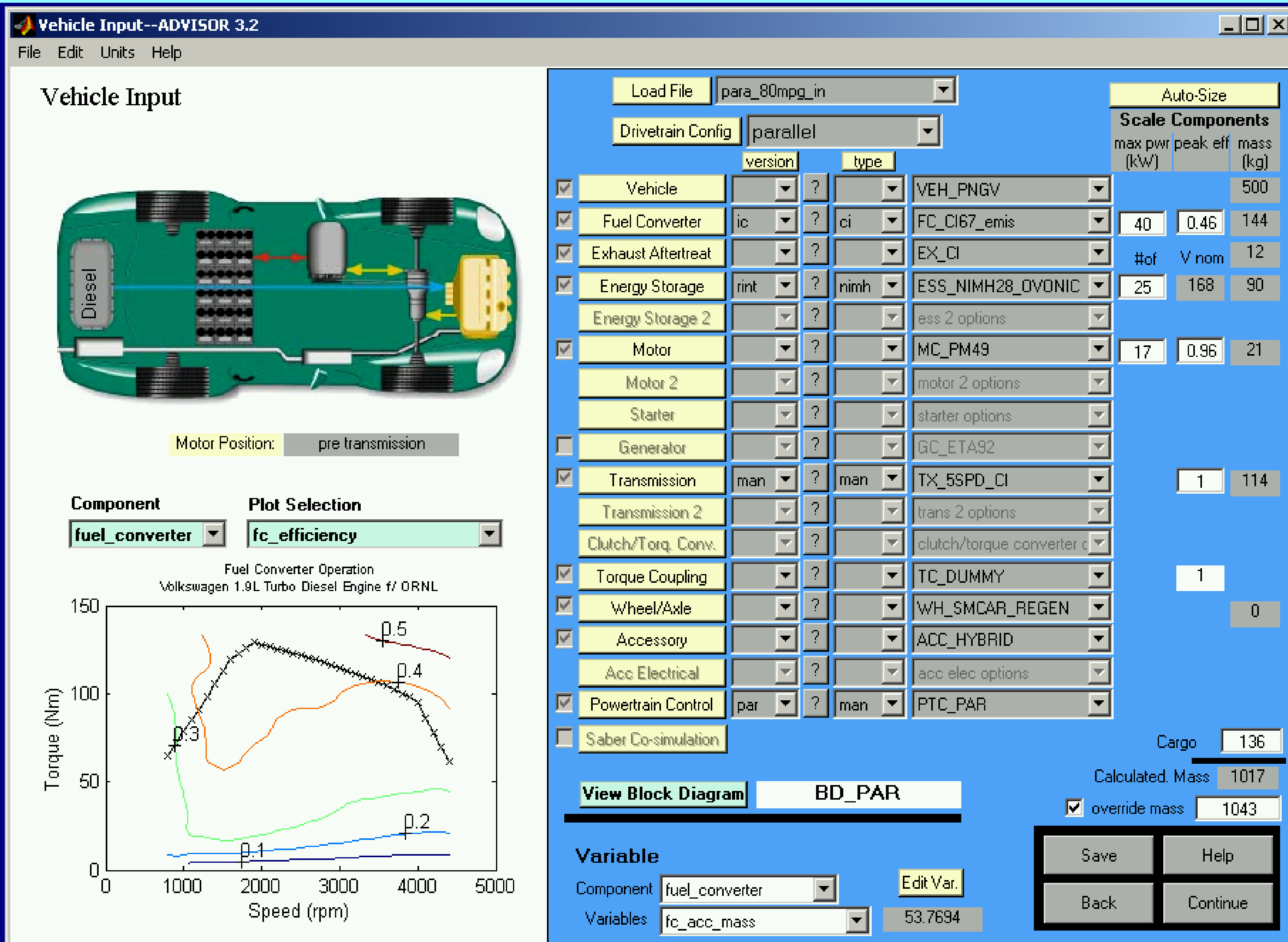
GUI



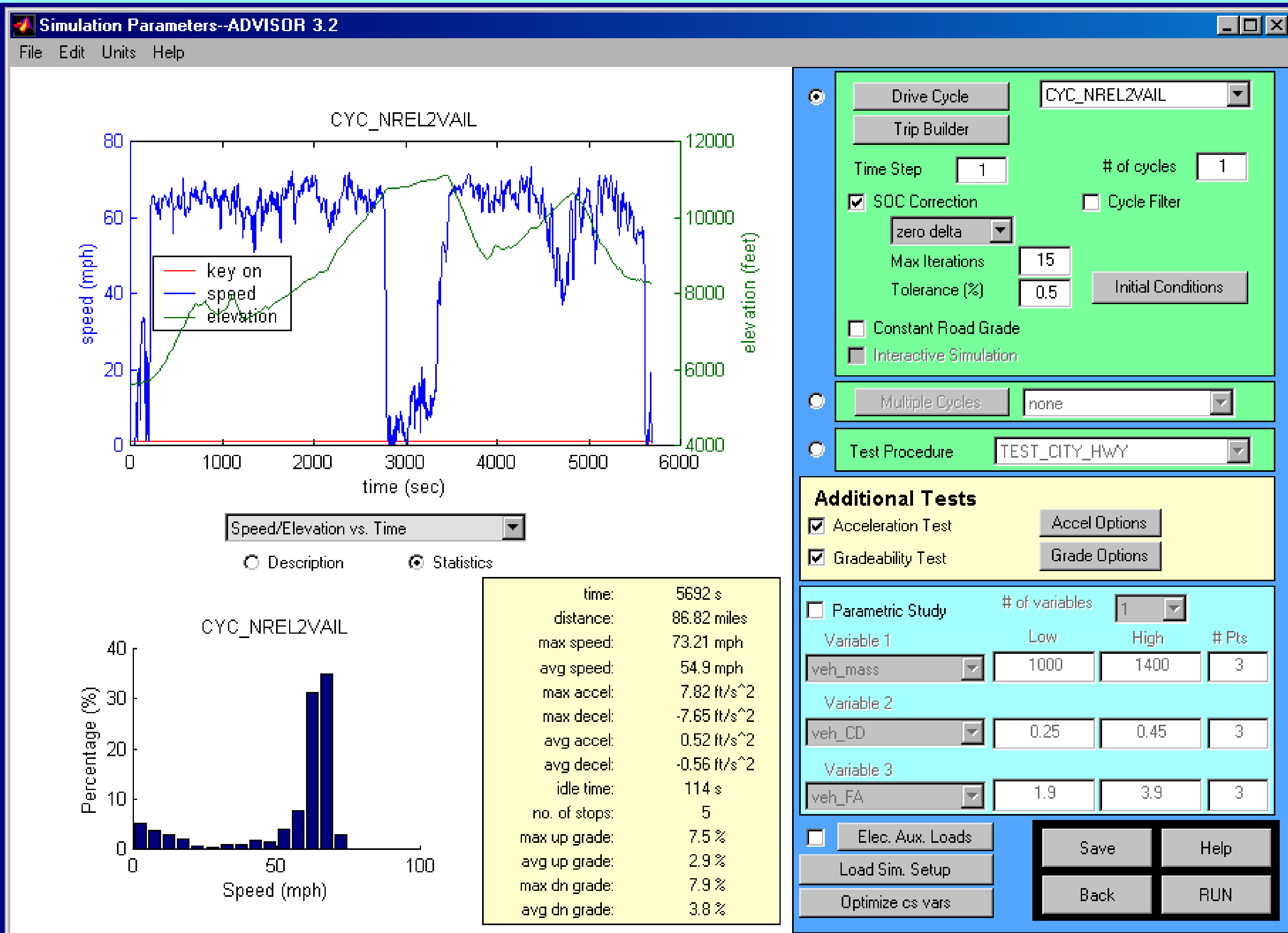



Data Files

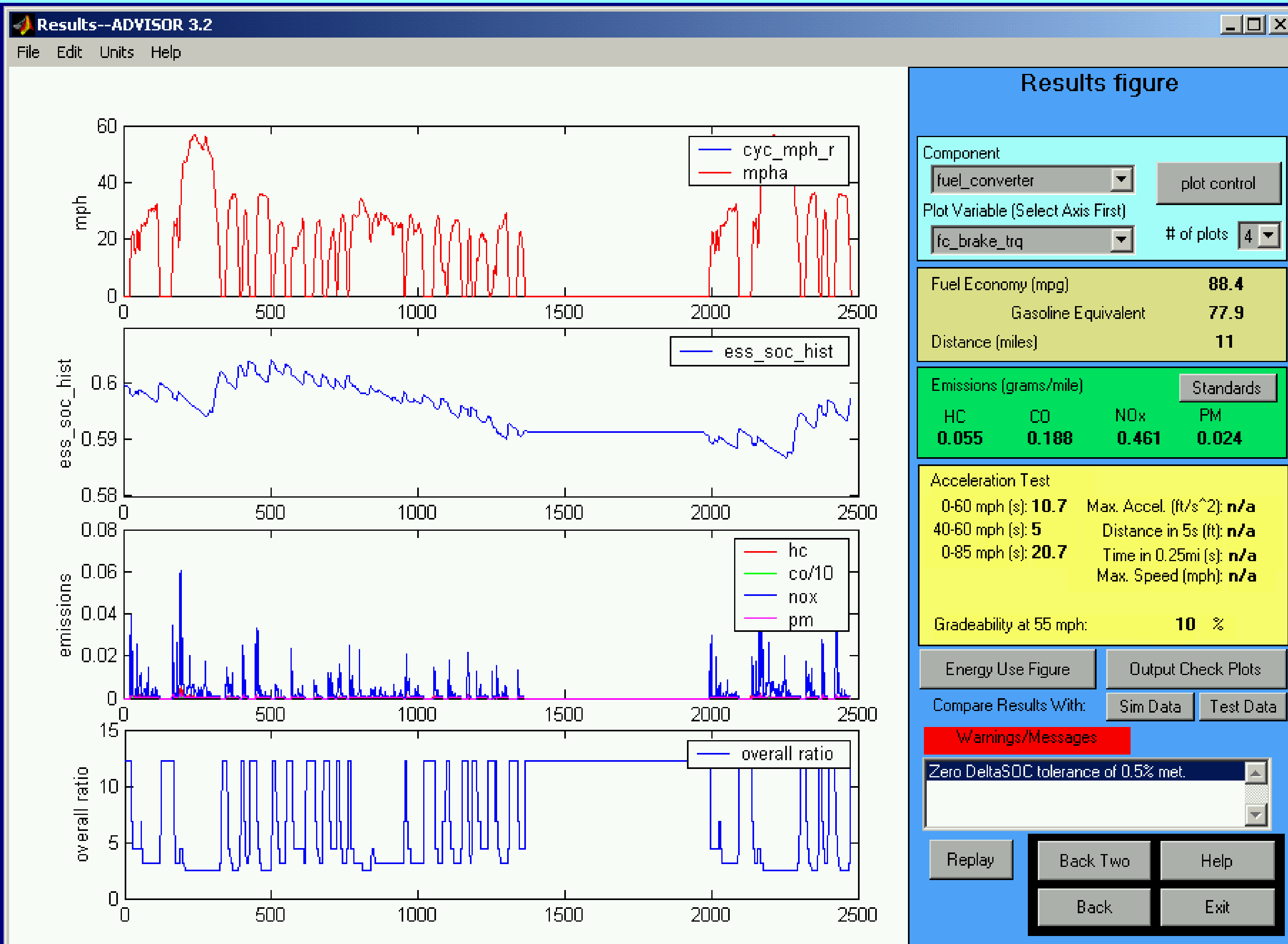
# Vehicle Input Screen



# Simulation Setup Screen

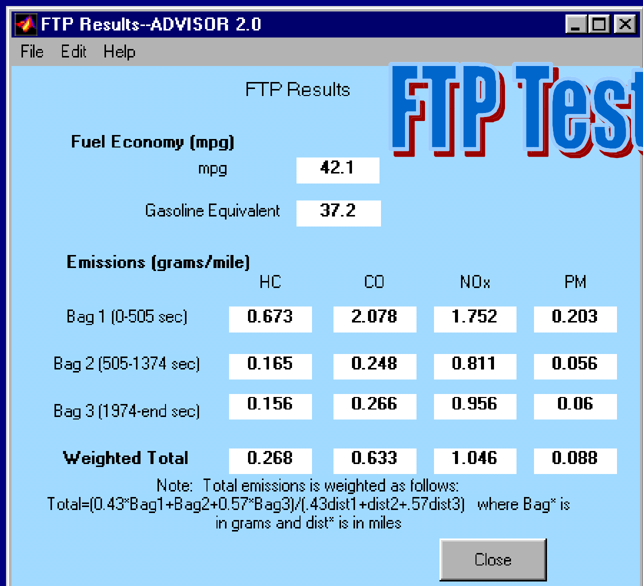


# Cycle Results Screen

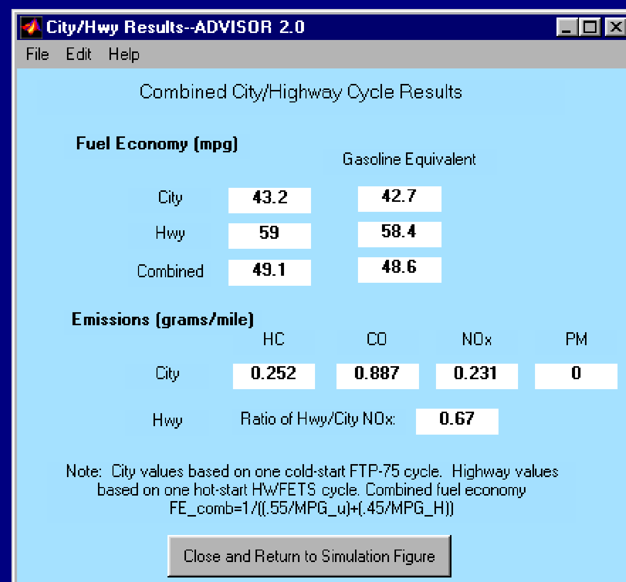


# "Test Procedures" Currently Available

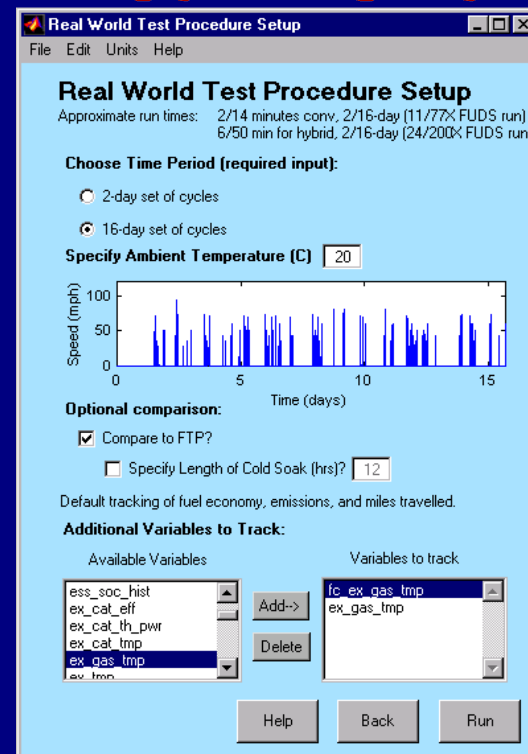
FTP Test



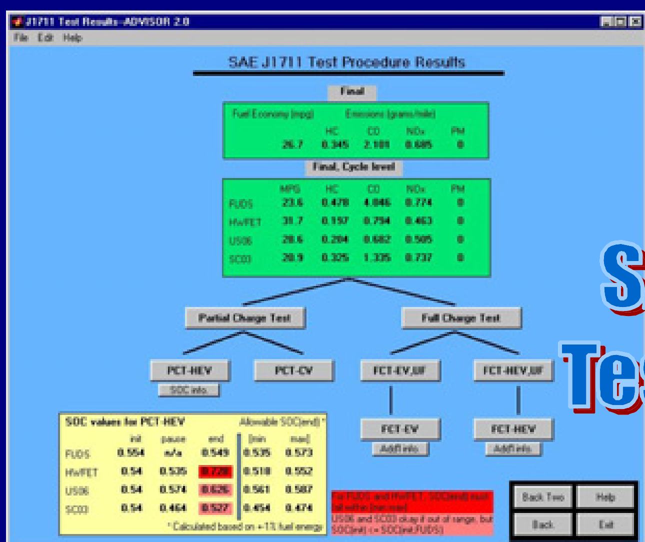

Combined City/Highway




Real World



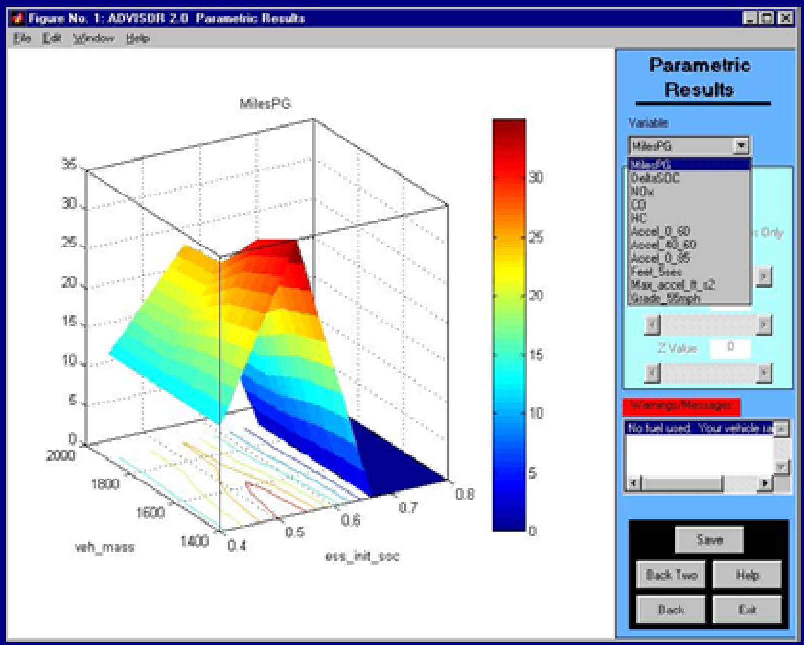

SAE J1711 HEV Test Procedure



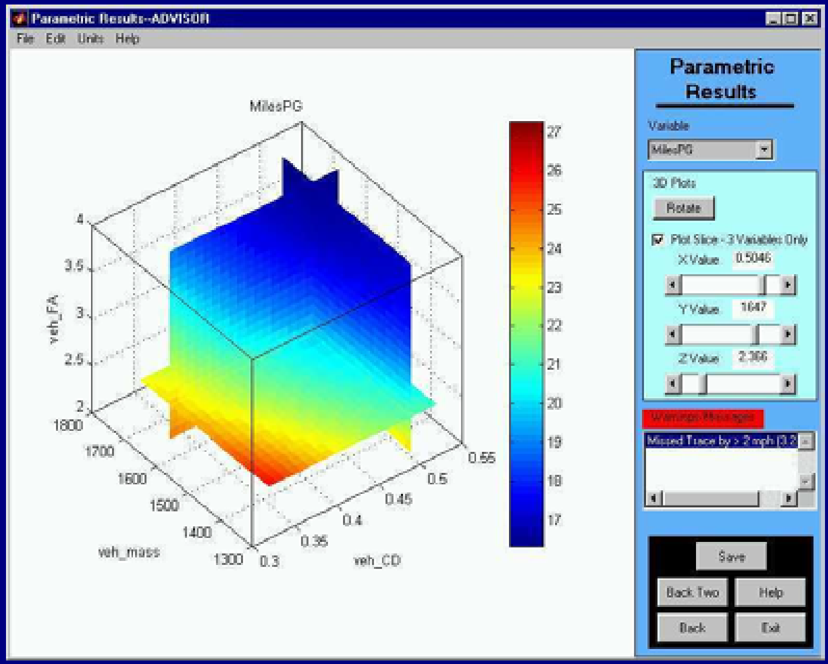

'Test procedures' save work and automate details of cold-start, bag weightings, etc.

# Fast Execution Time Enables Parametric Runs to Be Quickly Executed: 2D and 3D

Fuel economy, emissions, acceleration times, or achieved grade as a function of your chosen variables can be displayed



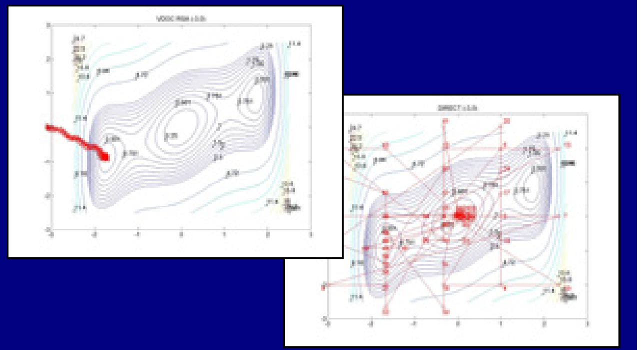

2 Variable Parametric Study



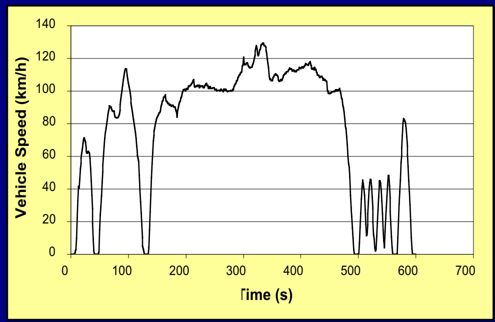

3 Variable Parametric Study

# Fuel Cell Vehicle Design Optimization Areas of Exploration

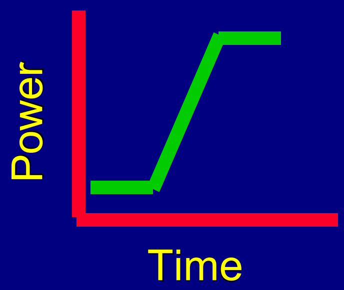
- Optimization Algorithms
  - efficiency of gradient and derivative-free algorithms



- Drive Cycle Impacts
  - Vehicle optimization for a drive cycle
  - Assessment of robustness of vehicle design

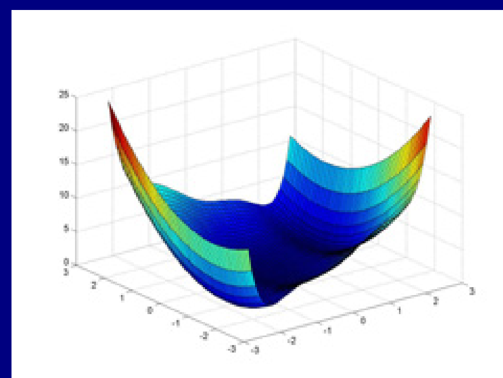


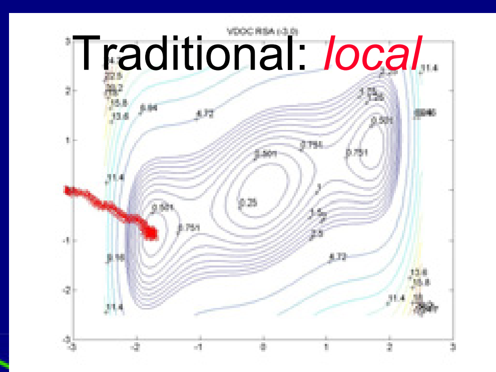

- Fuel Cell Systems Characteristics Impacts
  - Component characteristics drive system design

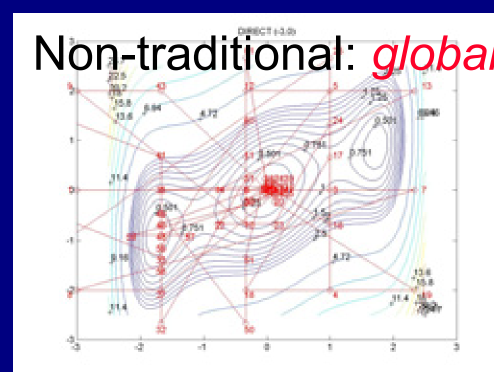


# Example of Applying Optimization Techniques
## *Fuel Cell Hybrid SUV*

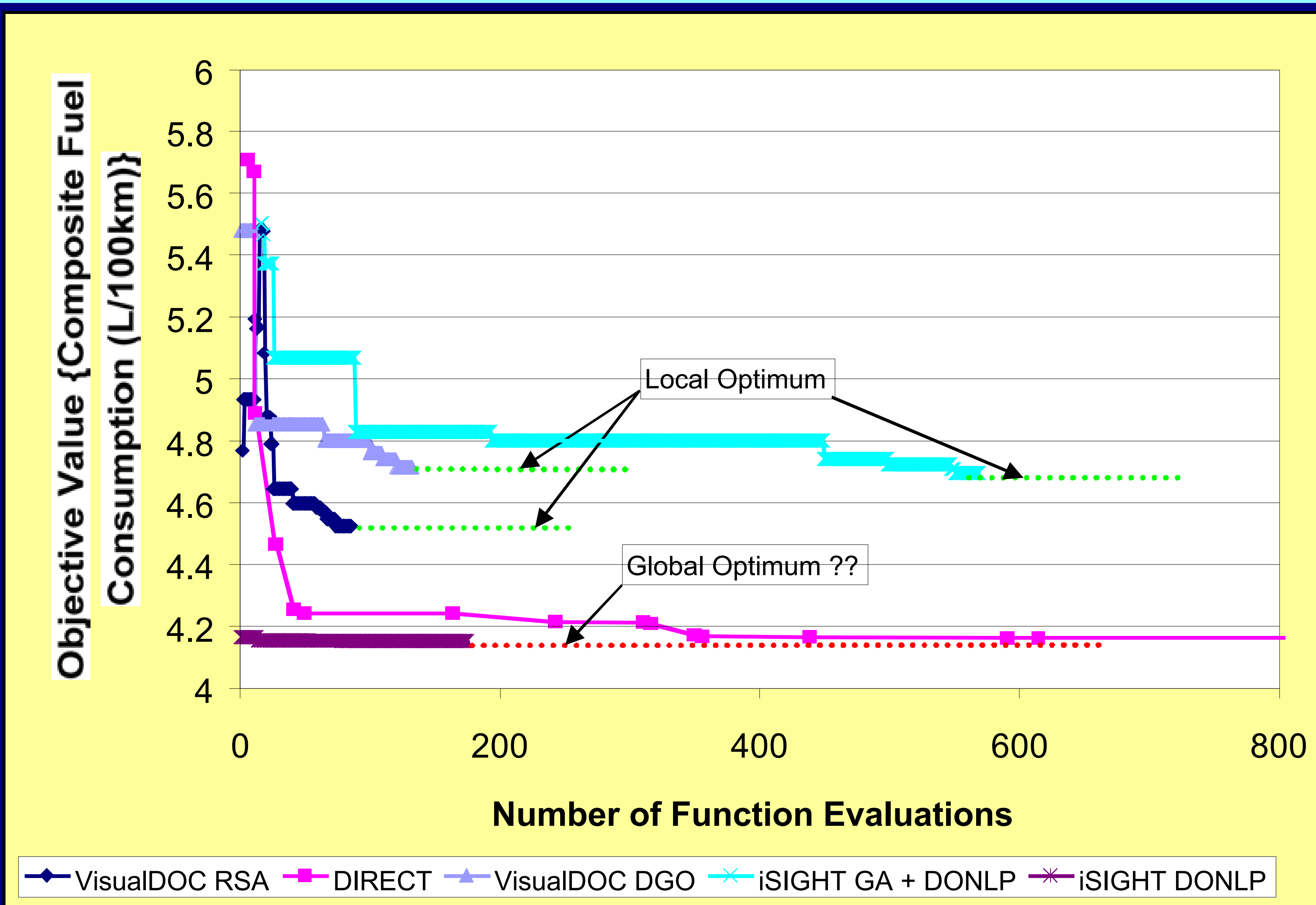
- Objective: Maximize fuel economy of Fuel Cell Hybrid SUV
- Optimizing coupled problem of sizing and control strategy leads to improved solution
- Multiple local optimums in HEV design space



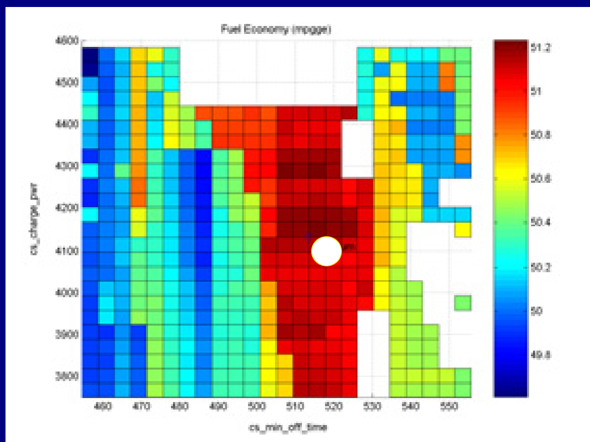


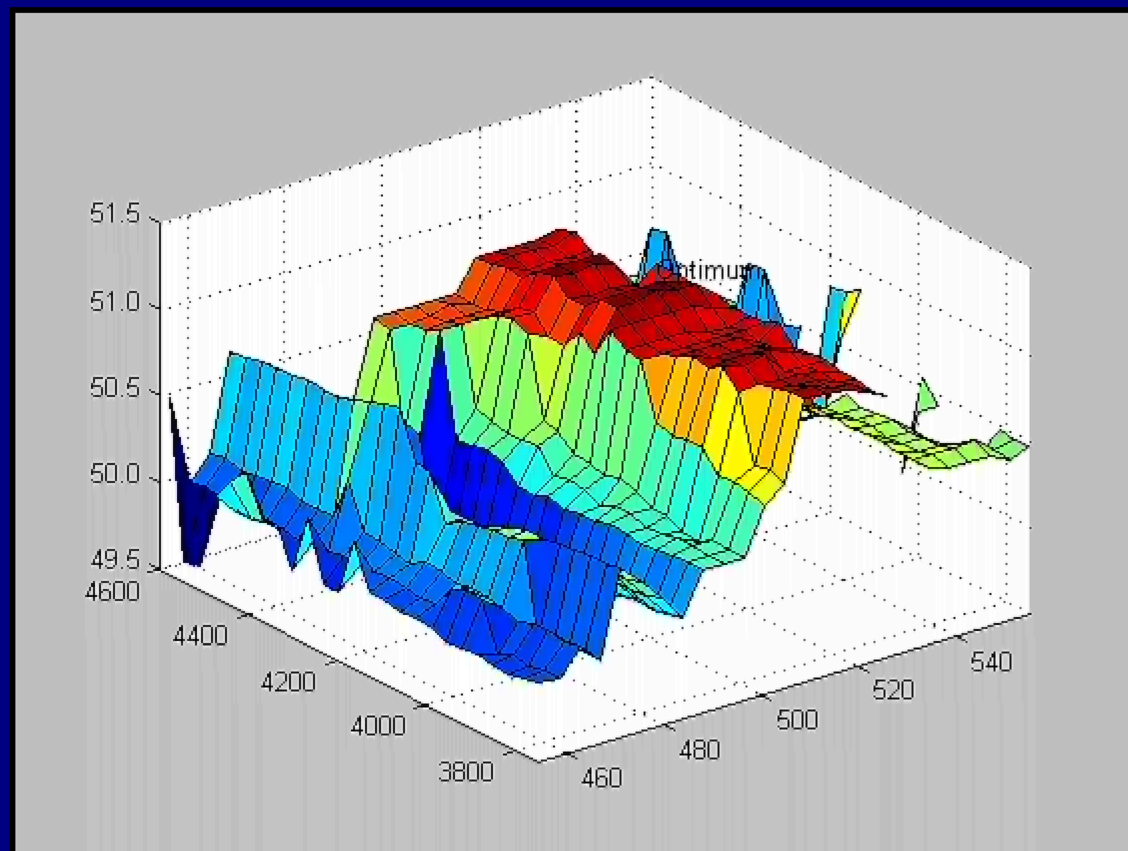



# Fuel Consumption vs. Function Evaluations -- Only DIRECT Does Not Get 'Stuck'



# Complex Design Space of HEVs
## Fuel Economy vs. 2 energy management parameters

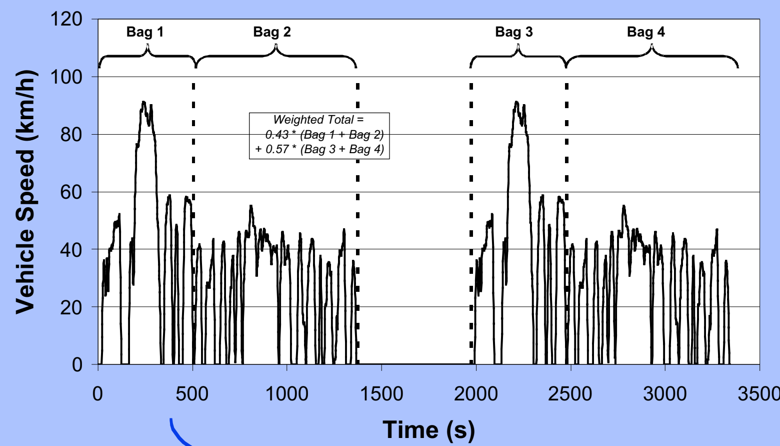


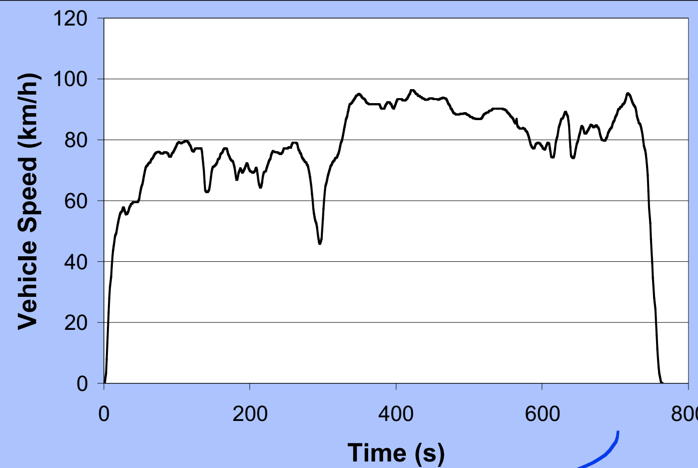




- Note:This only represents small portion (~1/25th) of 2 dimensions of an 8 dimensional space
- We are actually now doing parametric sweeps of these optimization problems (~3000 calls/per point)

# Drive Cycle Variation

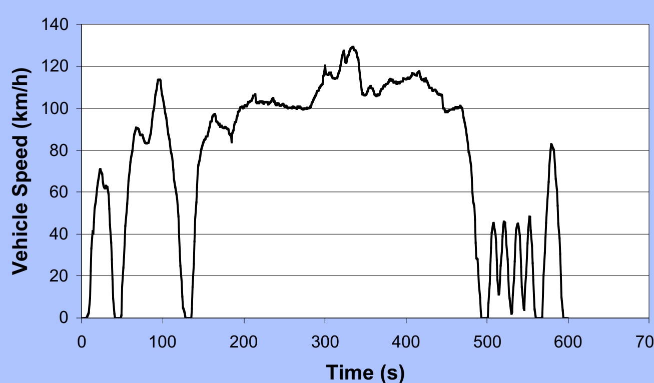
## 5 cycles Investigated (US city/highway are combined)



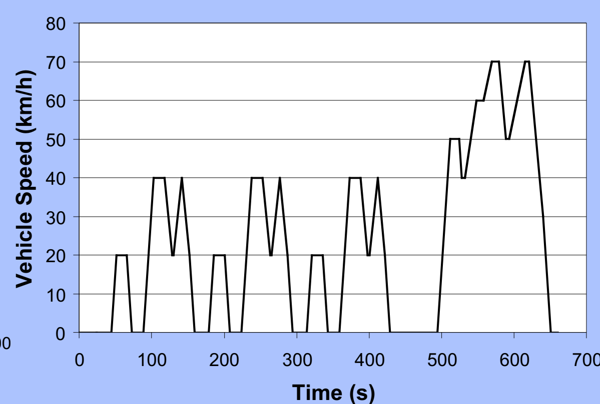




US city/highway combined cycle

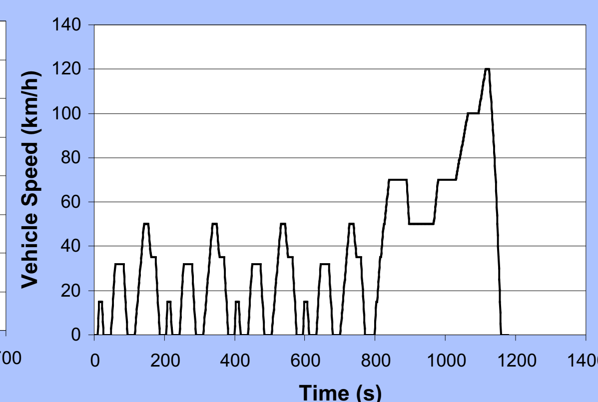
American US06



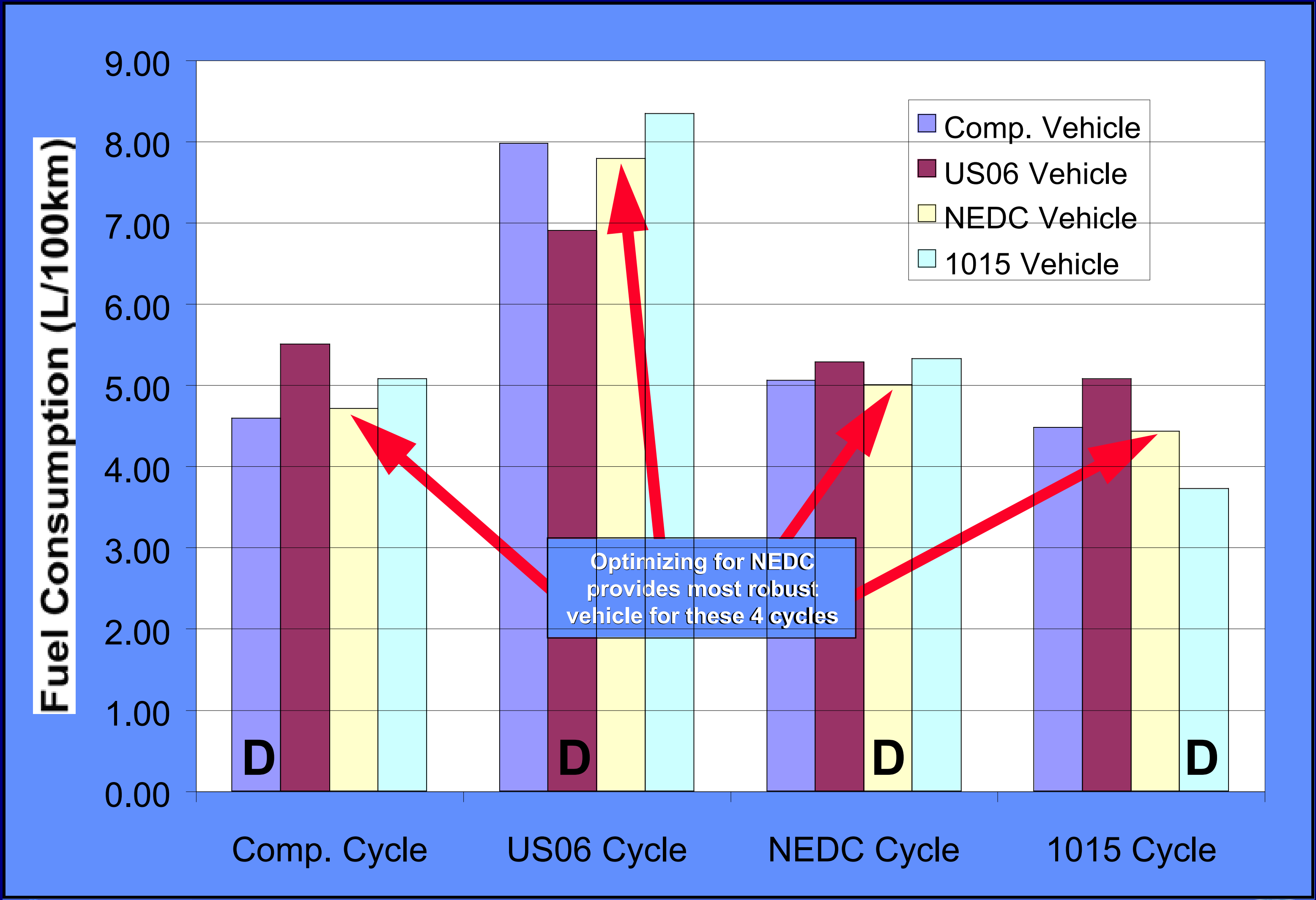

Japanese 10-15 mode



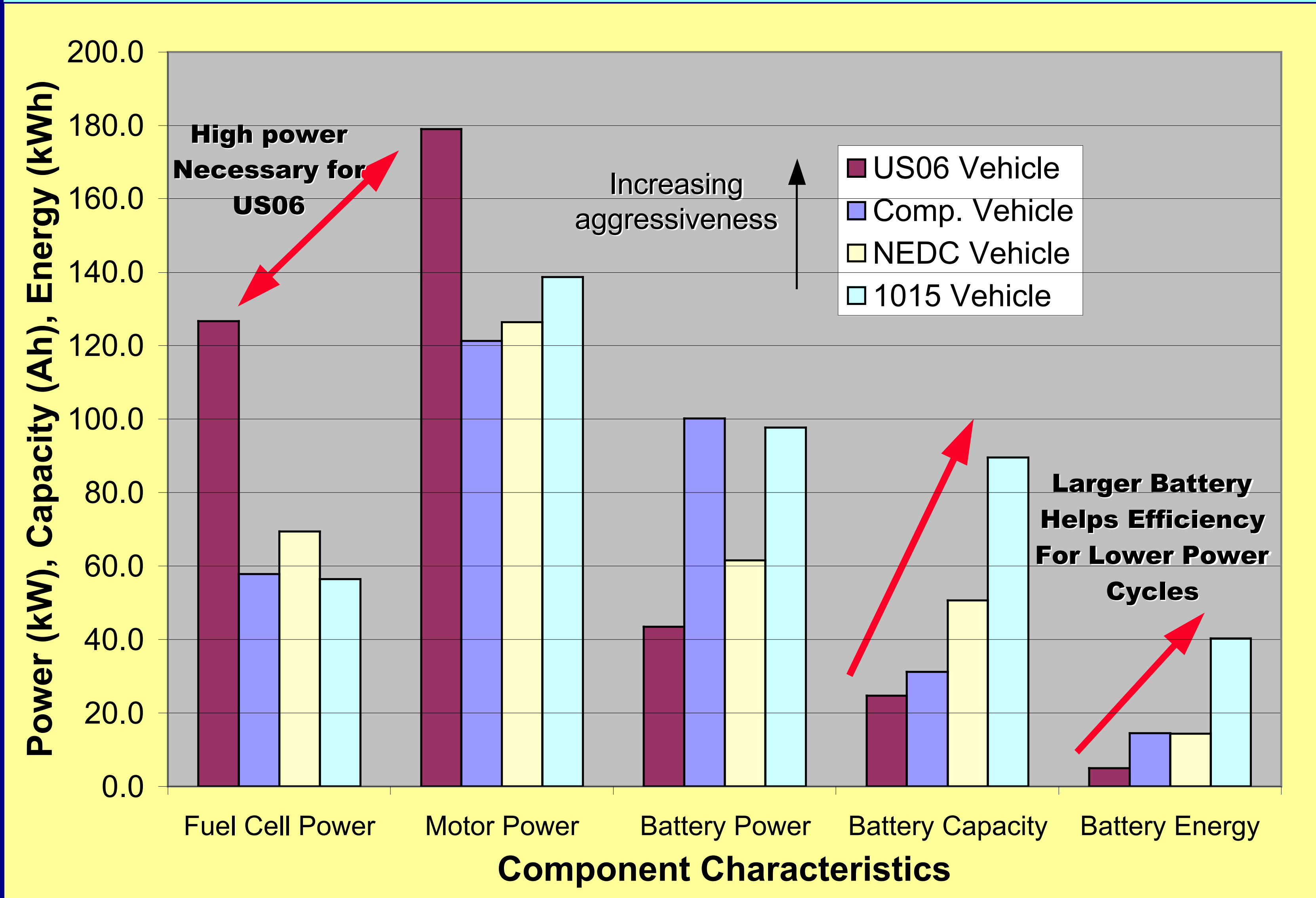

European NEDC



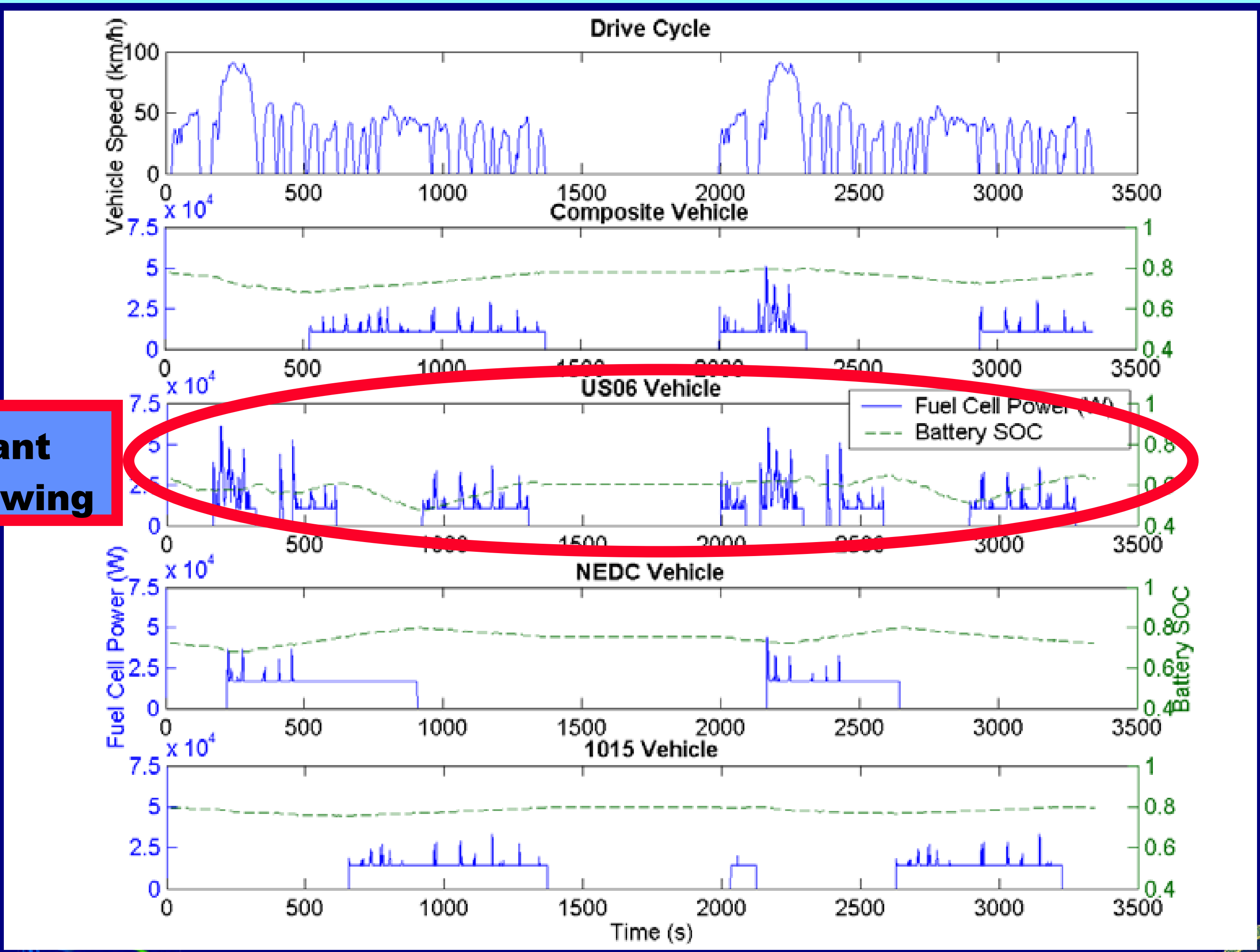
# Results: Drive Cycle Investigation (D = vehicle designed for this cycle)



# Characteristics of Components for Optimized Vehicles



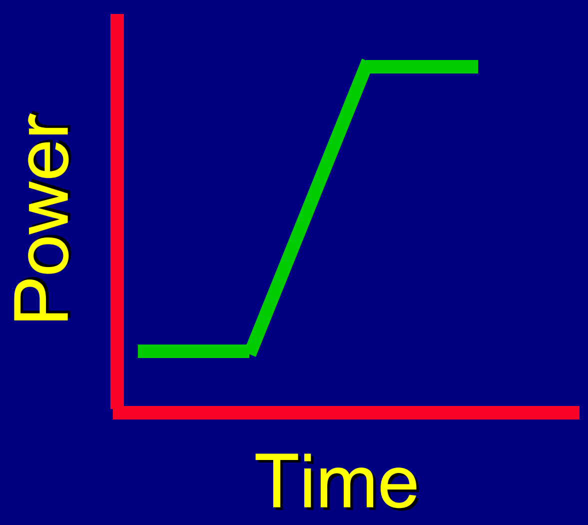
# Cycle Operating Characteristics on the 4 Cycles



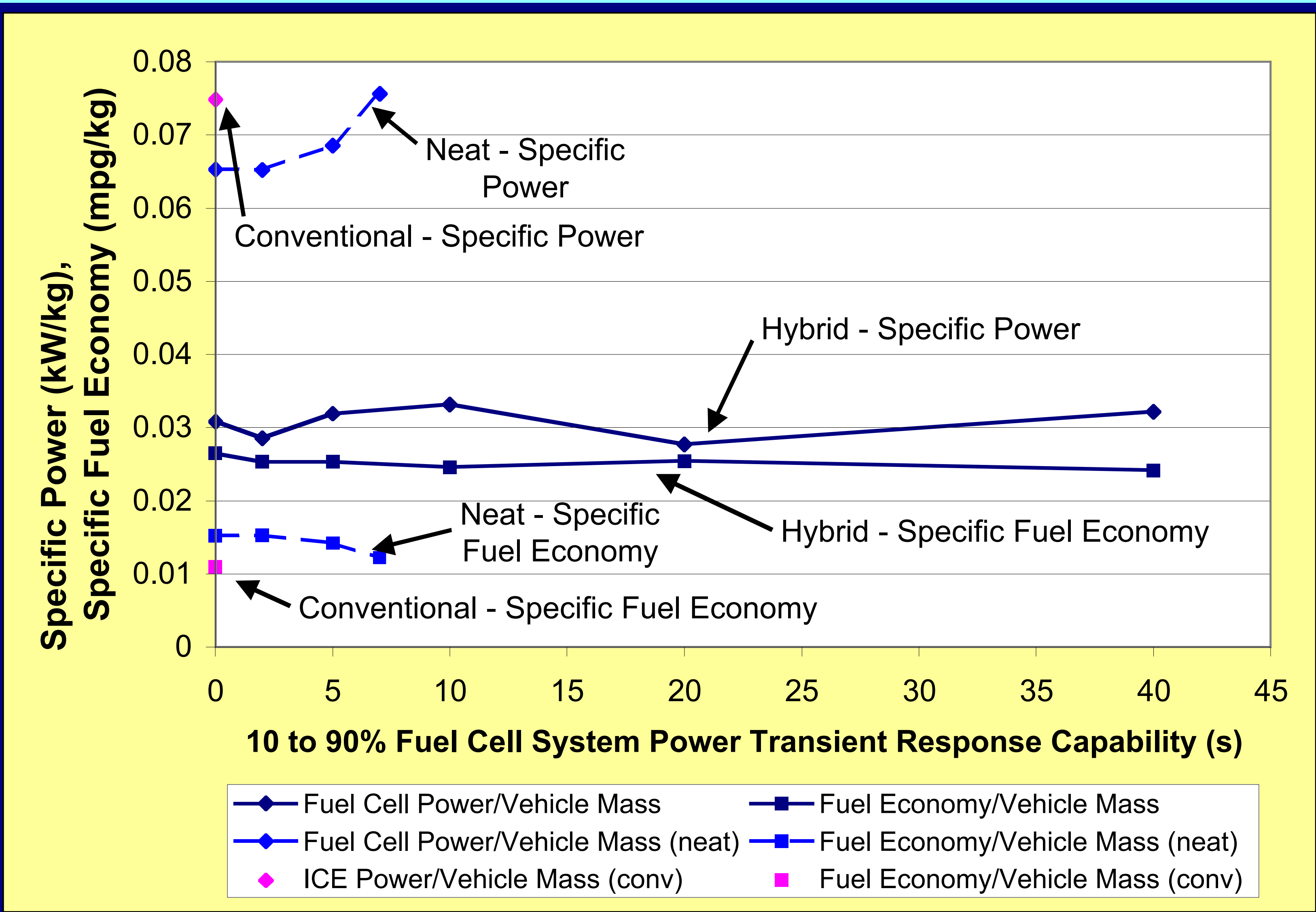

**Significant Load Following**

# Fuel Cell System Transient Response Study

- Vary the power response characteristics of the fuel cell system
  - 10-90% power in 0, 2, 5, 10, 20, and 40s
- Derived optimal vehicle configuration scenarios (component sizes and control strategy params)
  - Fuel cell hybrid vehicle
  - Neat fuel cell vehicle
  - Multiple drive cycles



# Comparison of Hybrid, Neat, and Conventional Vehicles



# Optimization of Fuel Cell Vehicle Design Provides Insight into System Trade-offs

2001-01-0236

Degree of Hybridization Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle

Paul Atwood, Stephen Gurski, and Douglas J. Nelson
Virginia Polytechnic Institute and State University, Blacksburg, VA

Keith B. Wipke

ABSTRACT

INTRODUCTION

Proceedings of IMECE:
International Mechanical Engineering Congress and Exposition
November 16, 2001 New York, New York

OPTIMIZATION TECHNIQUES FOR HYBRID ELECTRIC VEHICLE ANALYSIS USING ADVISOR

ABSTRACT

Optimizing Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV

Keith Wipke, Tony Markel, and Doug Nelson

Abstract

1 Introduction

2002 - FCC - 24

Vehicle System Impacts of Fuel Cell System Transient Response Capability

Tony Markel and Keith Wipke
National Renewable Energy Laboratory

Doug Nelson
Virginia Polytechnic University and State Institute

ABSTRACT

INTRODUCTION

- Coarse parametric sizing study indicated optimal fuel cell to system power ratio of 0.25-0.3 for fuel economy
- Determined that derivative-free optimization algorithms necessary for complex design space of HEVs
- Drive cycle influences optimal degree of hybridization and control parameters
  - NEDC provides robust design
- Fuel cell transient response capability critical for neat fuel cell vehicle
- An optimized hybrid design can nullify the effects of fuel cell transient response

# Key Industry Partners Involved

porvair fuel cell technology

UTC Fuel Cells
A United Technologies Company

Arthur D Little

AIR PRODUCTS

3M

GRUPPO DE NORA

Honeywell

gti

McDermott Technology, Inc.

NUVERA FUEL CELLS

Collaboration will help identify applicability and systems issues early in the R&D process.

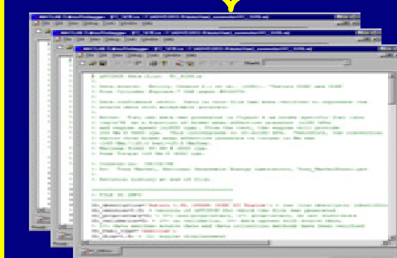
# Draw Upon All Available Sources to Gather Data and and New Models

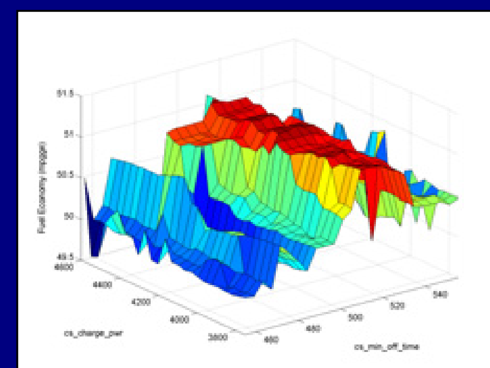
Test Data

**NREL, ORNL, ANL, Ford, GM, DaimlerChrysler, Delphi, Visteon, etc.**

Processing

**Power of DOE modeling approach is application of data and models!**






Modeling

ADVISOR 3.2
Advanced Vehicle Simulator

\+ Optimization